Master's Thesis

Master's degree in Energy Engineering

Optimization of PV power plant operation through energy storage providing ancillary services

REPORT

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ABSTRACT

Renewables are gaining importance in electrical grids and markets nowadays, and in parallel, they are subjected to more and more stringent requirements for their grid integration. One tool for this kind of energy sources to be integrated is the field of energy storage.

This project proposes a methodology for the economic optimization of the sizing of a battery bank, which enhances the participation of a PV power plant in network primary frequency support. Moreover, the energy storage system is used as a mean to minimise penalizations due to forecasting errors, made by the producer in the schedule of the energy that will be sold in the day-ahead market (DM).

The methodology consists in the formulation and the resolution of a Linear Programming (LP) problem, implemented in GAMS, applied to a 5 MW PV power plant, equipped with Nickel-Manganese-Cobalt (NMC) batteries, in the Spanish energy market. However, the primary frequency control analysis, is performed considering real data extrapolated from the UK market regulation, since in Spain, this type of service is mandatory, but not remunerated. The project aim is, therefore, the study of a near future scenario in which renewable producers are totally integrated in the electricity market and they could receive adequate remunerations for ancillary services support (as it is already enabled in the UK electricity market). For the forecasting error adjustment, instead, the Spanish deviations management market is taken into account, following its current legislations. Finally, data for solar power generation and batteries costs are estimated from literature.

Results suggest that the implementation of a battery bank represents a profitable solution for the provision of frequency response support, since the power plant can work near its maximum power point, increasing its total income of around 2.08 M€ (24% more) within 15 years (life time of the storage device). In order to enhance this service, the energy storage system should be sized at 345 kWh. The energy forecasting correction, instead, expects a battery bank of around 332 kWh, since the provision of both services make the battery charging and discharging at the same time, decreasing the final energy managed. With this configuration, the power plant producer is increasing the profits of about 280000 € (3% more), comparing with the case in which the power plant is not equipped with energy storage and the forecasting errors are not managed.

In conclusion, the implementation of batteries generates an economic improvement, increasing in both configurations the power plant income, thus considering the related initial investment totally warranted. Moreover, the use of an optimization software as GAMS avoids the risk of batteries over-dimensioning, which let be worth nothing the economic advantages obtained with ancillary services provision.

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1. INTRODUCTION

The gradual depletion of stocks of fossil fuels, the environmental pollution problem and the global climate changes have led governments all over the world to increase the penetration of renewable energy sources (RES) in the power system. Security of supply improvement, fossil fuel dependence reduction and greenhouse gas (GHG) emissions decrease are the main challenges of our time for the achievement of a sustainable society.

In order to reach these important goals, the European Union (EU), and in specific the Renewable Energy Directive, established in 2007 an overall policy for the production and promotion of energy from RES, known as European 20 20 20 Targets. This climate strategy set three main key targets: 20% cut in GHG emissions from 1990 levels, 20% of EU energy from renewables and 20% in energy efficiency, within 2020 [1]. In 2015, Europe GHG emissions were down by 22.1% compared with 1990 levels, so the EU is expected to succeed in this goal. Concerning the energy efficiency objective, EU has made substantial progress, since its 2020 target has already been achieved. Finally, renewable energies is on the rise in the EU providing 16.7% of gross final energy consumption in 2015 [2].

In Fig. 1.1, it is possible to analyse the improvements reached by Spain in the integration of renewables into the electric grid and their successful participation in the electricity production of the country (values in percentage) from 2009 to 2015.

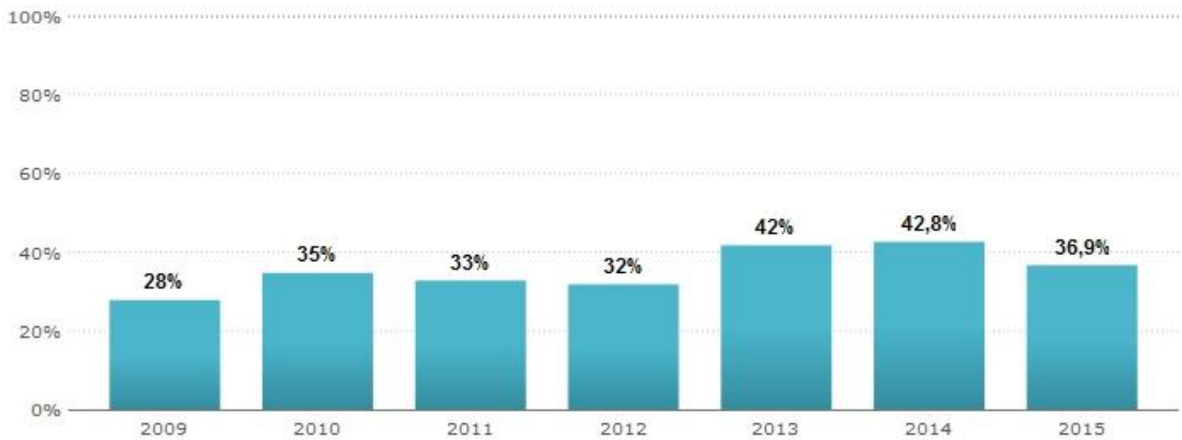

Fig. 1.1: Integration of renewables in the electric grid: Spanish scenario from 2009 to 2013 [3]

Among all, wind and solar photovoltaic (PV) power represent the fastest-growing technologies in the renewable energy domain. Concerning PV, solar energy generation rose by 6% in 2015. Similar to wind, it was trigged by an increase in capacity (+7%) and weather conditions, together with the dramatic reductions in cost of the solar panels in the last recent years. Within the EU, Germany, Italy and Spain represent the 71% of total European Network of Transmission System Operators for Electricity (ENTSO-E) solar generation (102 TWh) [4].

However, the intermittent nature of such power and its difficult prediction pose challenges for its integration into the electricity network. Huge efforts are being carrying out to increase the control of RES in different fields: technically, with advanced output power controls, regulatory, with exigent grid codes, and also by promoting the active participation of these installations in different electricity markets and ancillary services [5].

In interconnecting grids, one of the main concerns is the frequency regulation. In case of sudden variation, the system stability is ensured by the Primary Control Reserve (PCR) ancillary service. This type of control involves an automatic modulation of the generating plant output according to the frequency measured at the Point of Delivery (POD). In this way, PCR maintains the active power balance in the electrical power system immediately after network perturbations. Unfortunately, a RES based plant providing PCR has to intentionally decrease its production to be able to supply upward reserve in case of under-frequency. This means that the PV plant is wasting free renewable energy reducing the revenue during normal operation [6]. Hence, if the service remuneration from the ancillary service market is not enough to cover the losses, the profitability of the system will decrease.

Safety and quality of supply are strictly connected to the primary resource nature: many changes in grid codes have been implemented due to the fluctuating trend of the PV generation. Variations in irradiance caused by changes in clouds movement can cause extremely dangerous consequences. For very fast fluctuations, indeed, the Transmission System Operator (TSO) has a limited response capacity and, if the irradiance variation exceeds the permitted limits, then there is a risk of a complete power system failure.

Finally, another important concern is related to the participation of PV power plants in the electricity market, which is limited by the difficult prediction nature of the energy resource. The climate forecast, indeed, represents an important issue for the electricity sale, since the producer has to estimate a good forecast, as closer as possible to the real operation of the power plant. In case of prediction errors caused by a difference between the scheduled power generation and the effective power consumption, the producer incurs in economic penalization. This concept is still under study, since the reliability of the current prediction systems reveals being inadequate comparing with the mature technology of the traditional power plants.

Nowadays, the best promising technology to enable RES to offer ancillary services is the battery energy storage systems (BESS). Already implemented by many installations, this technology is able to mitigate the PV solar power intermittency and forecasting thanks to its flexibility and energy reserves. BESS mainly contributes to two main factors: the fulfilment of the grid codes by optimizing the PV plant production and the generation of controllable power, which reduces the variability of the plant output.

Indeed, BESS installations are able to manage the fluctuation problems caused by the clouds movement, which affects the reliability and the quality supply of the PV power plant in terms of grid stability, as well as the solar panel efficiency and lifespan. In order to smooth such variations, one of the simplest method which can be implemented is the ramp rate control strategy.

Moreover, the battery energy storage system can accumulate the surplus of energy generated in those periods in which solar production is higher than the power plant commitment and allows delivering it back in the opposite situation, when the production overcomes the demand. In other words, BESS can satisfy the technical requirements for primary frequency regulation by absorbing power from the grid for high frequency periods, above a nominal value, and injecting power to the grid during low frequency excursions, below nominal set point. Additionally, since BESS are composed only by static elements, they have a very fast dynamic response compared to typical generators or other storage devices [7]. This improvement offers the possibility for the power plant to participate in the electricity markets and, as a consequence, maximize revenues since the power plant can operate close to its nominal value, forecasting errors are minimized and no penalization costs are affecting the power plant profit.

Fig. 1.2 shows the current battery storage capacity on distribution networks, counting for 0.4 GW installed, set to increase up to 0.6 GW [8].

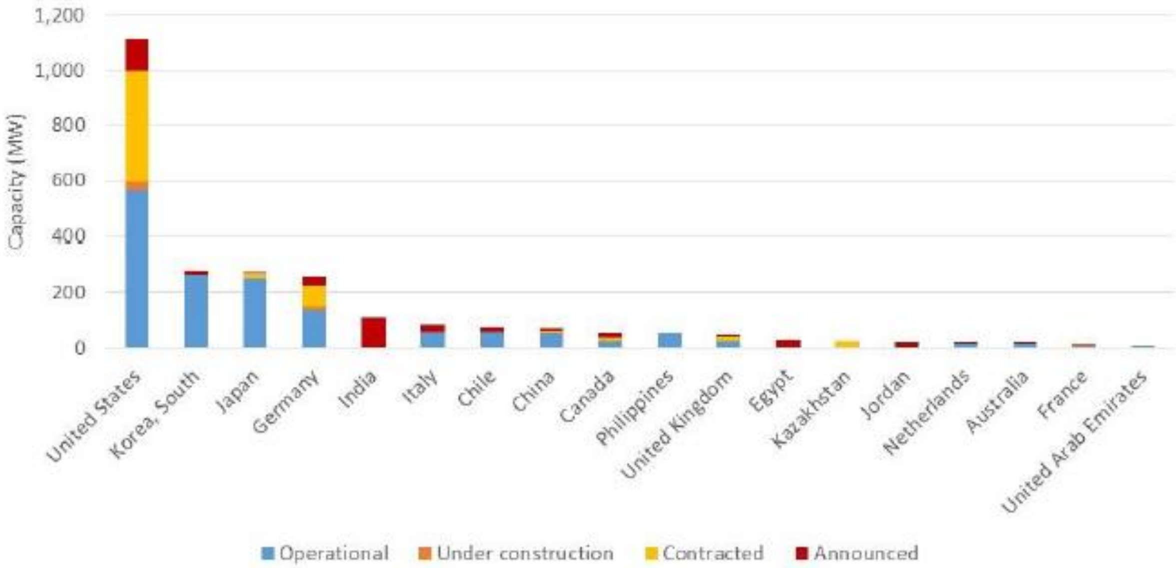

Fig. 1.2: Battery storage capacity (MW) on distribution networks in MV and below [8]

However, the installation of BEES has a major impact on the energy/economic balance of the PV system, playing a key role in the viability of the future PV system due to their high costs and reduced shelf life. As a result, parameters such as energy capacity, losses and the cycling degradation of the batteries take an important role. Any reduction in both the energy storage system capacity required and charge/discharge cycles will have a positive impact on reducing the investment required to install and maintain the energy storage system.

Many previous works have presented the implementation of an energy storage system for the optimization of the PV power plant operation, but the size of the batteries has been usually over-dimensioned. This concept has been developed focusing the attention only on the avoidance of the penalties imposed by the grid operator to the power plant in that cases of unexpected under-production (forecasting errors). The same idea has been followed for the ancillary services provision, both frequency regulation and ramp rate control: the battery size has been chosen for the main scope of providing power to the grid in the case of a sudden fault or frequency decrease in the power network and to compensate the fluctuations generated by the clouds movement. If on one hand this strategy avoids penalties and power losses for the PV plant production, thus increasing the revenue, on the other hand, the choice of an over-dimensioned energy storage system must face the huge investment related to the use of big batteries. The right compromise should be the implementation of an energy storage system with optimal batteries size come from the cost saving achievement reducing the size of the batteries, without occurring in economic penalties with a proper control and dispatch of energy.

The main goal of this study is to underline the benefits of the implementation of a battery energy storage system for a PV power plant, which could be able to manage weather forecasting errors and provide ancillary services, such as primary reserve response. This project proposes a strategy to guarantee the BESS optimal sizing, according to the regulations imposed by the power network under study, together with the optimal control of the PV power plant by managing the prevision problems associated to the unpredictability of the solar resource -which has always affected PV power plant competitiveness in the electricity market- (**Error! Reference source not found.**).

The optimization is applied with GAMS software through a mathematical linear programming problem in the design stage, to determine the optimal energy storage system size taking into account the provision of primary reserve for frequency regulation, as well as in the operation one, to optimally ensure the PV power plant participation in the electricity markets, avoiding forecasting errors and economical penalization, in order to maximise revenue.

This scenario explores data and regulatory framework taken from the Spanish market, considering the day-ahead and intraday configurations, but also the UK market, since the provision of primary reserve in Spain is a non-remunerated, mandatory ancillary service provided by generators. Although energy storage systems are considered as generator units while injecting electricity to the grid, there is not a clear and common framework to promote ancillary services for this category.

According to the aforementioned problem, this work consists in a demonstration project, which explores the use of energy storage system as ancillary services provider in a near future where a defined regulation is established and considered to optimally ensure the participation of PV power plants in the Spanish electricity markets. To do so, the UK market regulation is taken into account, where the primary frequency control provided by batteries is an adding value for the total income increase of the PV system, thanks to the remunerations received for this type of service.

Finally, the two methodologies implemented can be summarised as:

- "methodology for the optimisation of energy storage system for frequency support in PV power plants": considering the UK market regulation as base case (red blocks and arrows in Fig. 1.3);
- "batteries dimensioning of a PV power plant for the costs reductions of forecasting errors": based on the current Spanish market operation (blue arrows in Fig. 1.3).

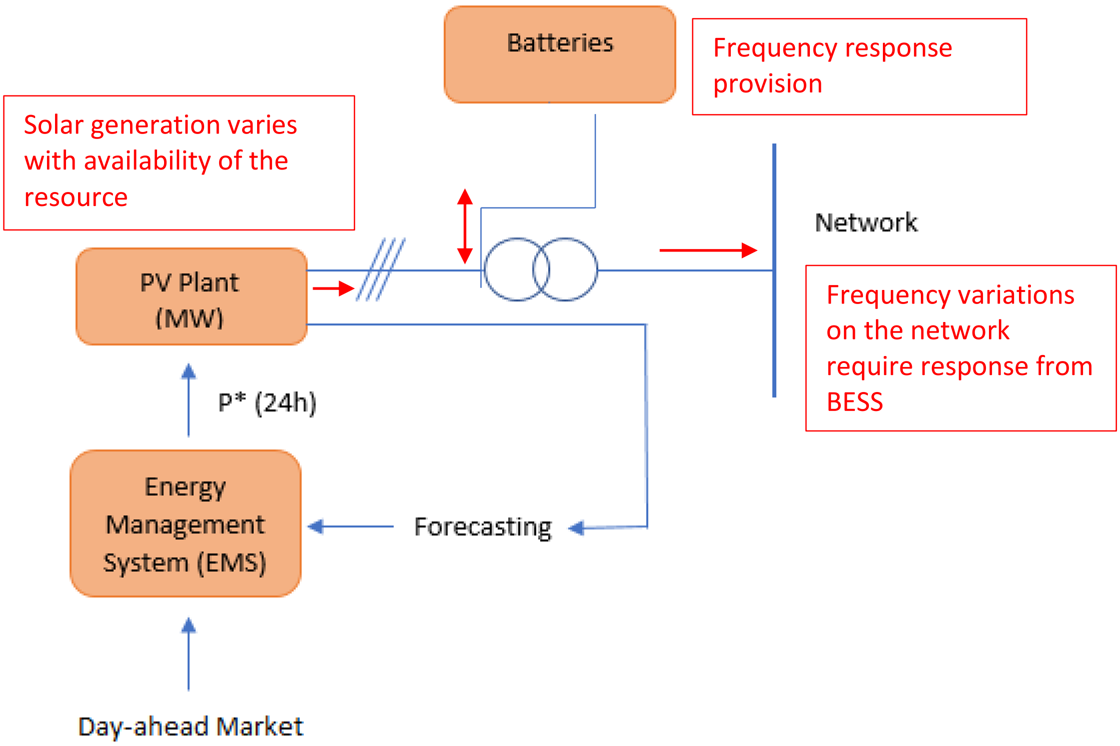

Fig. 1.3: Conceptual scheme of the system proposed

2. STATE OF THE ART

Many previous works state the problems related to the integration of renewables in the electric grid. The majority of them focuses the attention on the use of energy storage system to enhance the provision of ancillary services and improve the RES power plant competitiveness in the electricity market.

Concerning ancillary services provision, [9] studies the opportunities provided by the implementation of a BESS in a 50 MW wind power plant for primary reserve response. The aim of the work is the optimization of the economic income of the power plant by ensuring the complete exploitation of the wind resource, since the power plant can generate close to its maximum energy available, thanks to the use of energy storage device for frequency control and stabilization. However, the total income of the system is affected by the choice of the battery energy storage system size, due to the frequent choice of an over-dimensioned device, thus decreasing the power plant profitability. So, in order to maximize revenues, this project analyses the optimal batteries system dimensioning taking into account the economic benefits associated with the provision of primary reserve. The optimization process is developed through GAMS by maximizing the value of J, an objective function, which considers the capital and operational costs, income from the wholesale UK market and frequency response market; in this way, the optimal BESS size can be established.

A part from [9], there are many reports declaring the advantages of an energy storage system integrated in wind power plants for frequency response. However, concerning PV, it results more difficult to provide projects with photovoltaic power plants as ancillary services suppliers.

Other works, instead, analyse the advantages of installing a BESS in PV power plants to face the uncertainty problem of demand provision, as discussed in [10]. This project, indeed, examines the viability of a battery energy storage system for the costs reduction associated to forecasting errors of a 5 MW PV power plant. As previously said, in order to participate in the electricity market, the solar energy producer has to estimate a good prediction of the energy that he or she wants to sell in the market. If the forecast deviates from a pre-fixed error limit, the producer incurs in economic penalties, which decrease the overall profitability of the system. BESS is proposed as a solution: the optimal sizing configuration is performed through GAMS for two different situations, according to the Spanish electricity market regulation: the first one is the participation of the power plant only in the day-ahead market, while the second one offers the participation in the intraday market too.

Keeping analysing the state of the art, also [5] studies an optimal sizing and control of an Intelligent Photovoltaic (IPV) power plant based on the optimal participation on electricity markets. The project considers the daily and intraday markets, for maximizing the economical revenue of a 1.2 MW PV power plant located in Tudela (Navarre, Spain). As a consequence, the Spanish market has been examined. The optimization process is separated in two stages: the design stage aims to determine the optimal storage system sizing for obtaining the maximum economic revenue of the IPV power plant market participation. To do so, one year evaluation period is taken into account including in the Linear Programming (LP) optimization process the cost of the PV system, power electronics, batteries, replacements, operation and maintenance, together with the storage system behaviour. The second stage is the operation one, where the proposal process includes two steps related to the two electricity markets that the IPV power plant participates on. The optimization applied in both steps (generation planning for day-ahead market participation and online operation for the intraday market) considers a fixed storage system size, which is the output of the design stage. The results show an overall reduction in the energy storage system capacity, from 560 to 433 kWh. Furthermore, the control strategy for the optimal market participation increases around 20% the income of the power plant, thanks to the energy reserves provided from the storage system [5].

However, none of these strategies ([10] and [5]) takes into account the provision of primary frequency control, which could be an adding value for the power plant total income.

In the case of stand-alone systems, instead, one possible solution found in the literature [11] to optimise the energy storage system in order to satisfy the load demand is the combination of battery storage system together with ultracapacitors, in the common definition of Hybrid Energy Storage System (HESS). The optimization of the PV power plant has the main objective of avoid over/under design of the system, which could lead to increase system lifetime cost or unsatisfactory Loss of Power Supply Probability (LPSP), which is the probability that the PV panels and energy storage system are not capable of supply the load when required. In the HESS, the ultracapacitors are employed to supply the peak power requirements of the load with the average power supplied by the battery bank. Moreover, the ultracapacitors are given priority charging and can be charged from both the PV panels and the battery bank to ensure they contain adequate charge to supply the high power requirements of the load which can occur at any point. The optimization process is developed through Matlab and Simulink [11].

3. PRIMARY FREQUENCY CONTROL OPTIMIZATION MODELLING

This first methodology concerns the provision of primary reserve, made possible by the implementation of a battery energy storage system. The main objective is the determination of the optimal battery size in order to guarantee the maximum power plant income, obtained as a good compromise between the primary frequency control provision, whose remunerations increase the system income, and the choice of the battery size, since the dimension affects the investment needed to provide this type of service.

The implementation follows the methodology explained in **Error! Reference source not found.**, where the three main blocks are PV power plant, battery energy storage system and market and regulations. These entities represent constrains and input data that have to be taken into account for the formulation of the optimization process. In the following chapters a detailed explanation of each feature is described.

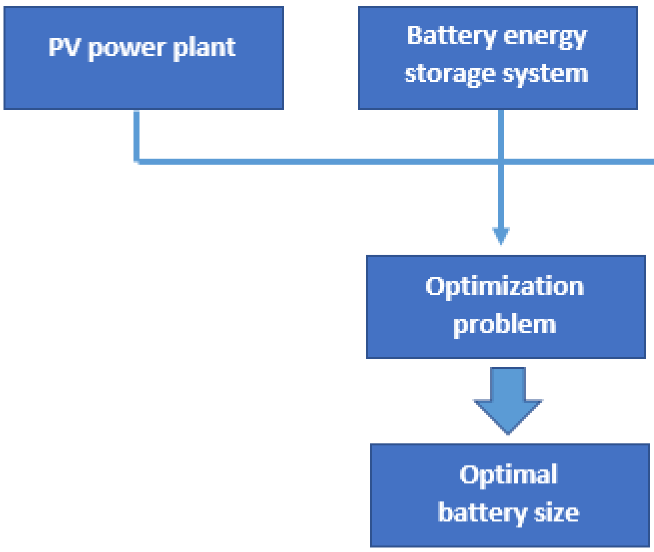

Fig. 3.1: Methodology applied

3.1. PV power plant

The PV power plant selected for the development of this work is characterised by a rated power of 5 MW. It is important to state that this installation is not physically existent, but it has been ideally constructed as to better fulfil the requirements needed for the implementation. It is supposed that the PV power plant is located in Spain, however, for simplicity, data and measurement are referred to other countries.

The first step which has to be followed is the determination of the solar irradiance that characterises a given site. National Renewable Energy Laboratory (NREL), located in Colorado, is a United State Department of Energy facility specialised in renewable energy and energy efficiency research and development. This entity performs many researches on PV and, therefore, it offers available data measured from the different sensors installed in the United States. From its database [12], solar radiation measurements can be extracted on a second-by-second basis. For simplicity, it is analysed the solar radiation related to one day selecting information every 15 seconds, reducing data to 5760 values. In order to construct an energy generation as real as possible, a mean of each interval composed by 15 values is calculated. With this method, the unrealistic probability of selecting a second in which a cloud may suddenly cover the panel is almost avoided; clouds movement, indeed, is not so fast to hide the solar panel for just one second, but it lasts at least few seconds before leaving the sensor surface.

The solar radiation ($\mathrm{Wh/m^2}$) correspondent to the selected day is shown in Fig. 3.2.

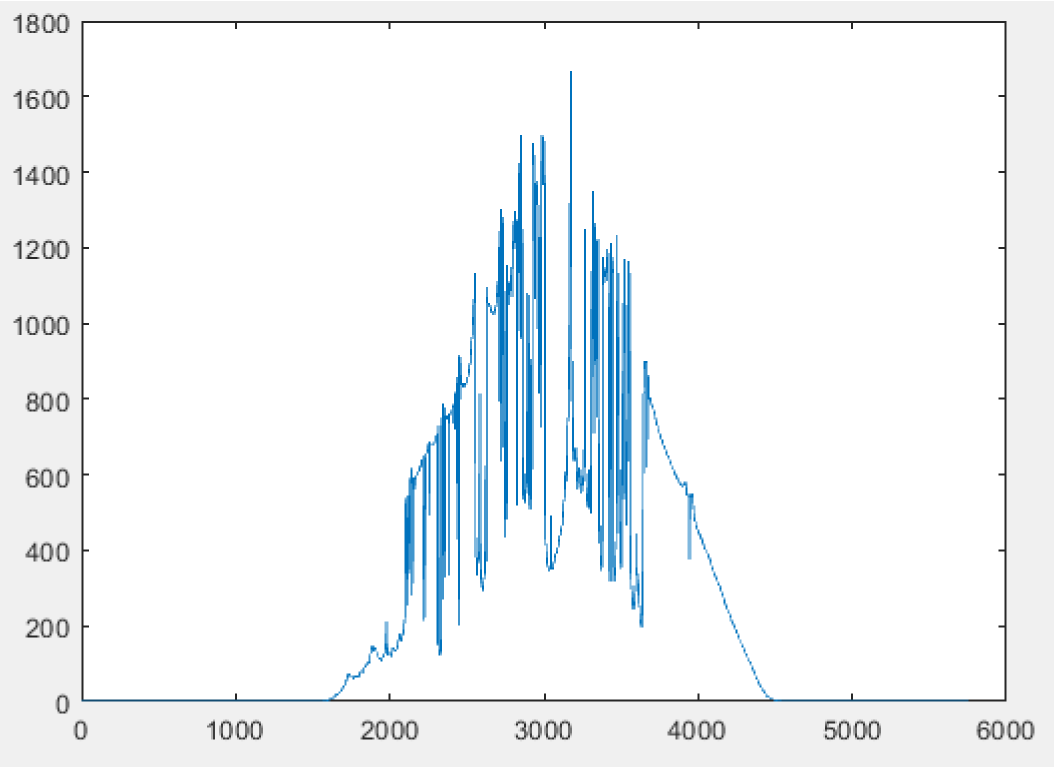

Fig. 3.2: Solar radiation for 19th March 2010 (Wh/m^2)

The corresponding energy generated by the power plant is built proportionally to the solar radiation. In order to adjust it to the rated power selected for the PV installation, first it is necessary to determine the common energy generated by a 5 MW power plant. Through the capacity factor (CF), which is the ratio of an actual electrical energy output over a given period of time to the maximum possible electrical energy output over that period, it is possible to determine the energy generated (Equation 3.1).

$$CF\ (\%) = \frac{Energy\ generated\ (\mathrm{MWh})}{Rated\ power\ (\mathrm{MW})\ \cdot hours\ of\ operation}$$

Equation 3.1

From this value, the solar radiation can be adjusted by multiplying it for a given value, *x*, which creates the 5 MW PV generation expected. For a PV power plant, the general capacity factor fluctuates between 10 and 30% [13]. In this case, a capacity factor of 29% has been chosen, resulting in an energy generated of 12745.8 MWh per year or 34.92 MWh per day. In order to determine *x*, the following equations are implemented (Equation 3.2 and Equation 3.3)

$$Energy\ generated\ (\mathrm{Wh}) = Solar\ radiation\ (\frac{\mathrm{Wh}}{\mathrm{m}^2}) \times x$$

Equation 3.2

$$x = N_p \times Surface\ (\mathrm{m}^2) \times \eta_{panel} \times \eta_{inverter} \times \eta_{transf}$$

Equation 3.3

where:

- N_p is the number of solar panel which composes the PV farm;
- $Surface$ is the area occupied by a single solar panel, around 2 m^2 [14];
- η_{panel} is the efficiency of the solar panel, 16-17% for multicrystalline silicon cell [14];
- $\eta_{inverter}$ is the efficiency of the inverter used to convert the DC-AC power, around 95% [15];
- η_{transf} is the efficiency of the transformer connected between the PV power plant and the network, around 97% [16].

All these parameters contribute to the calculation of *X*: knowing the values of these parameters, it is possible to determine first N_p, which is the only unknown, and finally *x* (Equation 3.4).

$$N_p = \frac{34.92\frac{\mathrm{MWh}}{\mathrm{day}}}{1.5\frac{\frac{\mathrm{MWh}}{\mathrm{m}^2}}{\mathrm{day}}\times 2m^2 \times 0.95 \times 0.97 \times 0.15} = 84.14 \approx 85 \rightarrow \qquad x = 23.3$$

Equation 3.4

Finally, the daily adjusted energy generated by the PV power plant is shown graphically every 15 seconds in Fig. 3.3. The PV generation fluctuates between 0 and 38.784 kWh.

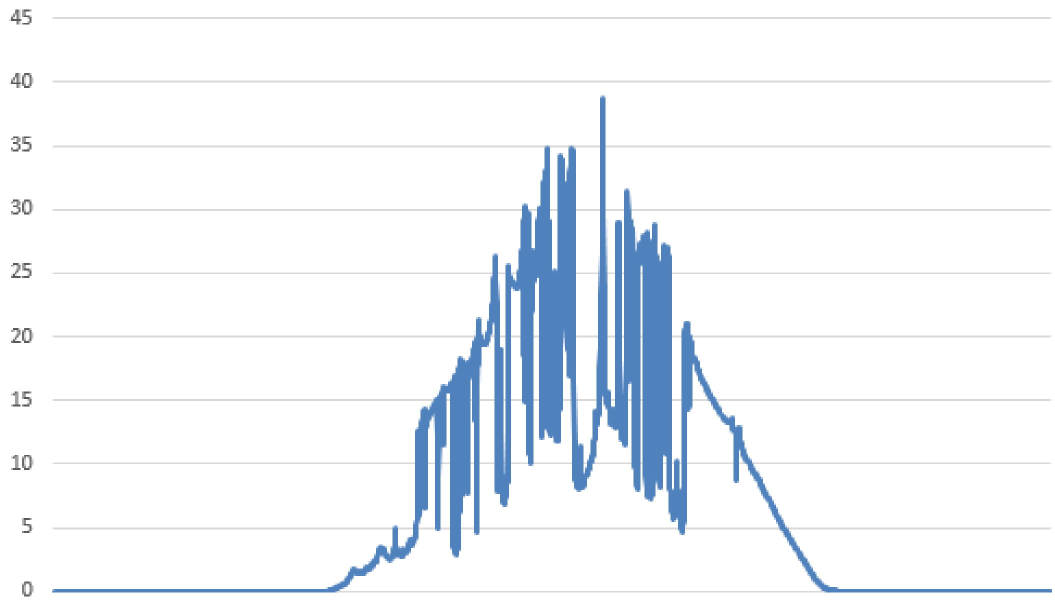

Fig. 3.3: PV generation every 15 s in a day (kWh)

3.2. Battery energy storage system

The energy storage device chosen for the implementation of this project is represented by a battery energy storage system. As previously said, this type of technology plays an important role in PV power plants by controlling the output power and providing ancillary services, such as ramp rate control and frequency regulation, enabling an increased penetration of PV power in the system.

First of all, it will be analysed the main operation principles of secondary batteries, describing in details how they work. Furthermore, in order to select the most suitable configuration for the project, a review of several available types of batteries for PV applications is evaluated. The main four technologies under study are:

- Lead-acid (LA);
- Alkaline;
- Molten salt;
- Lithium-ion (Li-ion).

3.2.1. Operational principle

Secondary batteries main property is the electrochemical reversible conversion of reduction and oxidation (REDOX): the first reaction permits to an element gaining electrons, while the second one consists in the loss of electrons. Furthermore, REDOX reactions involve non-negative electrochemical components, known as ions.

The reaction takes place under a determined condition within a cell composed by:

- Two electrodes: a negative one, called anode, and a positive one, called cathode. While discharged, oxidation reaction occurs in the anode of the battery, which is the electrode capturing the electrons lost by the component. Conversely, the reduction reaction occurs in the cathode, which is the electrode providing the electrons gained by the reduced component [17].
- Two pairs of electrochemical active substances: one in the anolyte region and the other in the catholyte one. The materials composing the anolyte electrode and the component surrounding it have to react yielding an oxidation reaction, while the electrochemical interaction which involves the catholyte electrode and the substance surrounding it yields a reduction reaction [17].
- The electrolyte: solid or liquid electronically insulating substance, which enables the transport of ions exchanged between the active substances.
- The separator: its objective is the avoidance of the direct contact between the electrochemical active substances, preventing the battery from an internal short-circuit.

Fig. 3.4 describes the operating principle of a battery cell. As it can be seen, the two electrodes are represented by two materials named Y0 for the anode and X0 for the cathode. The anode is surrounding by the substance Y1, while the cathode by X1. Materials X0-X1 and Y0-Y1 define two pairs of electrochemical active substances, whose energy difference is translated in a voltage different. The voltage between the cell electrodes (1-4 V) is known as open circuit voltage while charged; by adding an external load between the electrodes (circuit closed), the battery is being discharged and the redox reactions start, yielding an electrical current through the load [18].

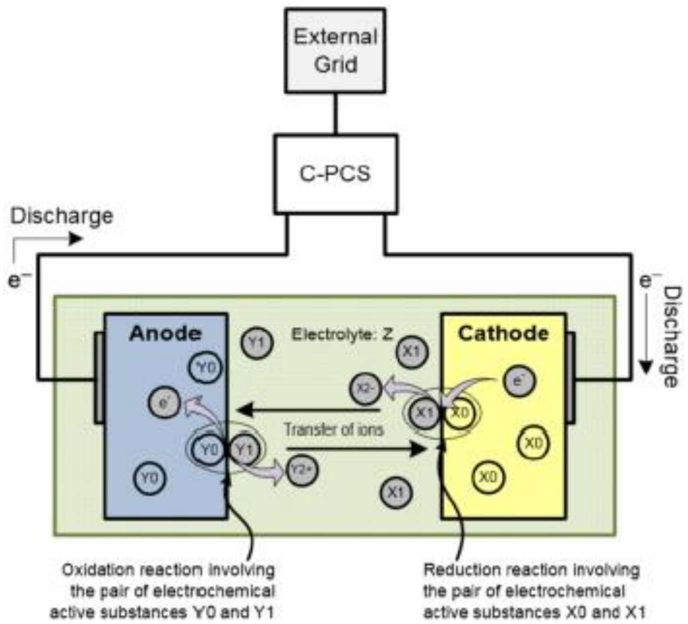

Fig. 3.4: Battery cell description [18]

3.2.2. Type of batteries

The following batteries are compared according to some main features, which represent key factors in the selection of the most convenient type of device depending on the producer necessities. They can be summarised in: specific energy, technology maturity, environmental impact, cost, efficiency, self-discharge, cyclability and working temperature.

Lead-Acid (LA)

In terms of energy density and cyclability, this battery type provides low performances compared with the other classes, however, its high maturity, low maintenance and low cost are considered its main advantages.

An important aspect that has to be considered is the sulfation: it consists in a degradation process which occurs as crystallization of sulphur acid in the cell electrodes, which causes the decrease of the capacity and lifetime of the battery. A possible solution can be its periodically overcharging (up to its 100%) applying continued charging voltages during hours for two times per month, thus dissolving crystals and recovering the cell capacity. Nevertheless, due to the high voltages applied, the aqueous electrolyte reacts in electrolysis generating hydrogen, which must be expelled for safety reasons. Furthermore, electrolysis oxides the electrodes decreasing the cell performances and lifetime.

LA battery operation is strictly dependent from the working temperature, which affects its performance. In previous studies, the cell temperature management has still been defined as the biggest challenge for this type of technologies, above all on the use of LA battery for frequency regulation. The required high power ramp for the provision of frequency stability causes temperature variations up to 8°C within cells in series [19]. These temperature deviations deeply affect the lifetime of the battery.

Their application takes place in auto-motion (vehicles start-up), stationary systems as Uninterrupted Feeding Systems (SAIs) or industrial activations.

Finally, in Table 3.1, it is possible to observe a summary of the principle characteristics of LA batteries.

Table 3.1: Characteristics of LA batteries [20]

Voltage	1.75-2.23 V (2.04 V rated)
Working temperature	-40 – 50 °C (25°C rated)
Cyclability	1800 (at 80% DoD, C/8)
Self-discharge	2-4 %
Efficiency	70-80 %
Specific energy	24 Wh/kg

Alkaline

Between alkaline batteries, the Nickel-Cadmium (NiCd) and Nickel Metal Hydride (NiMH) types are considered the most used. They offer a low voltage cell, but energy density and working temperature range higher than the LA batteries. Their most important drawback is the low cyclability and high price (up to 10 times the cost of the LA type). Moreover, this class of battery is affected by the "memory effect", which obstructs the correct operation of the cell reducing its lifetime. However, it is important to highlight that a favourable characteristic of alkaline batteries is their ultra-rapid charge, since the chemical reactions while charging are endothermic. For the NiMH type, the charging processes are exothermic (while the discharge ones are endothermic). Moreover, in case of overcharge, the cell temperature and pressure can considerably raise resulting in consistent lifetime and capacity loss.

Alkaline batteries find their application in stationary systems, such as emergency lighting, instrumentation and control, but also in large scale systems for renewable integration. Their principle characteristics are shown in Table 3.2, in particular the case of NICd ones.

Table 3.2: Characteristics of a NiCd battery [20]

Voltage	0.9-1.5 V (1.3 V rated)
Working temperature	-20 – 60 °C (20°C rated)
Cyclability	800 (at 80% DoD, C/8)
Self-discharge	10 %
Efficiency	60-80 %
Specific energy	47 Wh/kg

Molten salt

The main difference between the molten salt batteries and the others is that in this case the electrodes are liquid, contrary to the solid ones which characterise the LA, alkaline and Li types.

Currently in the market it is possible to find two different redox: sodium-sulfur (NaS), manufactured by a Japanese company since 2015, and sodium-metal chloride (Na/NiCl2), developed since the 70s. Both types offer high specific energy, efficiency and cyclability. Another positive feature is the non-dependence of these batteries from the working temperature: extreme ambient conditions do not affect their performance. However, in order to stand high temperatures, molten salt batteries need long pre heating, up to 24 h. Generally, the battery is being kept pre heated, but this type of process consequently requires high amount of energy, which can reach up to 15% of the energy stored in the battery per day. Nevertheless, in frequent discharge processes, the energy produced by the electrochemical reactions is enough to keep a correct working temperature.

Concerning their applications, molten salt batteries are mainly used in telecommunication, renewable integration and tertiary sector systems. In Table 3.3, the main characteristics of NaS batteries are summarised.

Table 3.3: Characteristics of NaS batteries [20]

Voltage	2.3-1.6 V (2.1 V rated)
Working temperature	300 – 350 °C (300°C rated)
Cyclability	4500 (at 80% DoD, C/8)
Self-discharge	0 %
Efficiency	89 %
Specific energy	122 Wh/kg

Lithium-ion (Li)

The Li batteries are the main character for the current energy transition from decarbonisation in different fields: among all, the transportation sector and the electrical power system. Focusing the attention on the second one, Li batteries offer excellent technical performances for the storage of intermittent electricity produced by renewable energies large and small scale power plants. Previous works have estimated the equivalent tons of lithium carbonate demanded in 2001, around 7467, for batteries applied to hybrid electrical vehicles and electrical power systems. The forecast made sees an increase up to 212401 equivalent tons of lithium carbonate for 2020 (27.3% increase between 2011 and 2025) [19].

Concerning the main features, Li batteries are characterised by high specific energy and power, high cyclability and low self-discharge. Nevertheless, this technology still has to overcome some barriers, such as the high cost, short cell lifetime and energy capacity. The price problem may be solved according to the redox improvement: Tesla Motors achieved a reduction of 60% in its electrical vehicles price adopting this strategy with LiNiCoAlO2 (80% Nickel, 15% Cobalt, 5% Aluminium) [21]. Indeed, anode and cathode can be used in a multitude of materials (as shown in Fig. 3.5): the current most manufactured material for the anode is graphene, however, for the cathode, there are many different options.

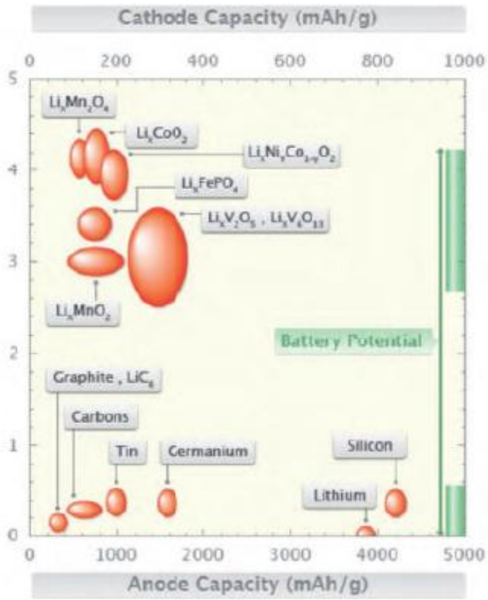

Fig. 3.5: Specific energy for different anode and cathode components for Li batteries [19]

The first batteries introduced in the market were the ones with Li_xCoO_2 cathodes, at the beginning of the 90s from Sony. They are principally used in mobile phones and cameras, exploiting their high energy density and cell voltage. For large scale applications, this type of Li battery is not so favourable due to the high cost of cobalt, whose resources are nowadays limited on earth.

The $LiMn_2O_4$ cathode batteries, also known as Lithium-manganese-oxide (LMO), were commercialised in the middle of the 90s with the improvement of presenting higher thermal stability. However, one main drawback is their low cyclability and energy density, which restrict their applications in high power peaks but during a short time period (traction systems for instance).

At the end of the first decade of the current century XXI, batteries with $Li_xNi_yCo_{1-y}O_2$ cathodes, also known as Nickel-manganese-cobalt (NMC), were introduced for large scale applications, thanks to their high specific energy feature. The high cyclability and the charge and discharge ratio performances allow the reduction of the cobalt used, which has been combined with other less expensive metals while retaining structural stability. For this reason, NMC cells are a common choice for stationary applications and the electromobility sector [22].

Finally, the Li_xFePO_4 ones are currently attracting the market, since they offer high cyclability and charge and discharge ratio. The lower cell voltage allows higher thermodynamic stability of the electrode respect to the electrolyte, thus improving security. For these reasons, this technology is favourable for large scale stationary applications, together with the electro mobility field.

In Table 3.4, it is possible to observe a summary of the main characteristics of NMC batteries.

Table 3.4: NMC batteries main characteristics [20] [23] [22]

Voltage	3-4.2 V (3.7 V rated)
Working temperature	-20 – 55 °C (25°C rated)
Cyclability	3000 (at 80% DoD, C/8)
Self-discharge	5 %
Efficiency	95 %
Specific energy	150-220 Wh/kg

3.2.3. Battery selection

In this section, the battery used for the implementation of the study is discussed. The choice is made taking into account all the characteristics described in the previous section and comparing them to better establish the most convenient one for frequency response application. In Fig. 3.6, it is possible to observe a comparison between the four types of battery analysed; as it can be seen, the more circular the radio is, the more performances the battery offers. Following this methodology, the battery with highest benefits seems to be the Lithium-ion one.

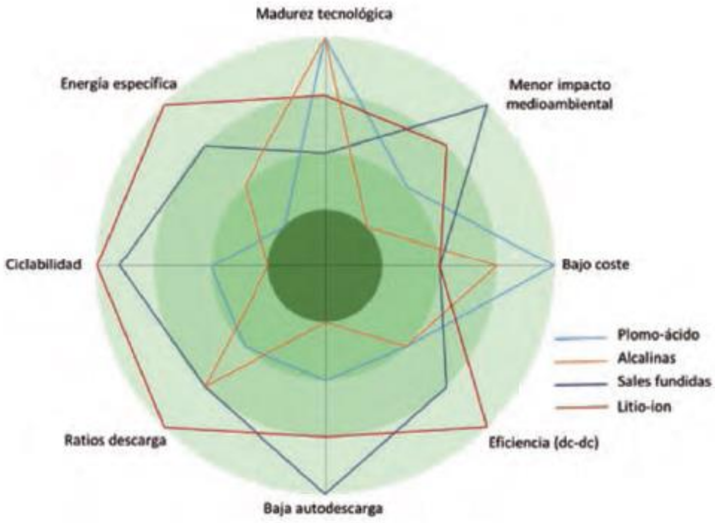

Fig. 3.6: Qualitative comparison between batteries [19]

A part from the performance characteristics, the environmental impact is also one main concern which has to be taken into account. Comparing LA with Li batteries, which represent the ones with higher performances, in terms of environmental impact, the Li ones result to be "greener" than the LA ones. This is due to the absence of heavy metals such as cadmium, lead and mercury whose levels have to be kept below a determined limit established by the EU Battery Directive. Furthermore, the higher efficiency offered by Li batteries ensures less operating losses, which represent the energy used to keep the battery charged. The 90-95% efficiency of the Li ones over the 70-80% of the LA type, together with the lower self-discharge offered by the Li batteries represent key elements for why Lithium-ion technology is more environmentally friendly.

Focusing the attention on the type of application for which the batteries are performed, in the **Lead-Acid (LA)** section, it is clear stated that their limited working temperature strictly affects their performance in the field of frequency regulation, where fast and high power rates are required to be provided for network stability assurance. As already mentioned, this requirement produces temperature increases which deeply affect the cell lifetime. Moreover, it is important to argue that, as described in the **Lithium-ion (Li)** section, their main application is in the field of integration of renewables for intermittency power output stabilization.

Concerning costs, Fig. 3.7 shows prices forecast of the different types of battery. As it can be seen, the lithium-ion one are expected to dramatically decrease between 2020-2030, making them even more attractive.

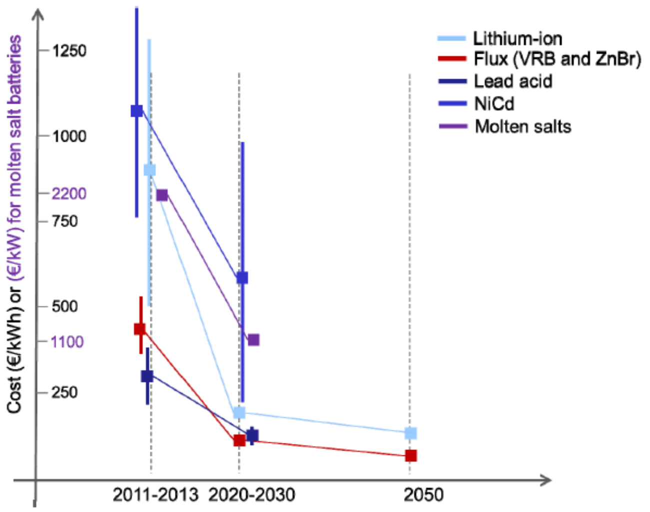

Fig. 3.7: Capital cost battery forecast [19]

For the aforementioned reasons, the battery selected for the project under development is the Li one, especially the NMC type. As shown in Fig. 3.8, indeed, the majority of battery storage capacity on distribution networks (MV and below) is from Lithium-ion batteries, around 70% [8]. The device implemented in this work is the use of a centralized AC coupling battery energy storage system: a big device connected to the point of control of the PV power plant. Instead of using a DC coupling configuration, which involves different energy storage systems for each array of the PV plant, the AC coupling represents just one device for the entire installation, which decreases power output fluctuations. This strategy is known as oversizing and takes into account the all power plant, instead of single PV panels arrays [24].

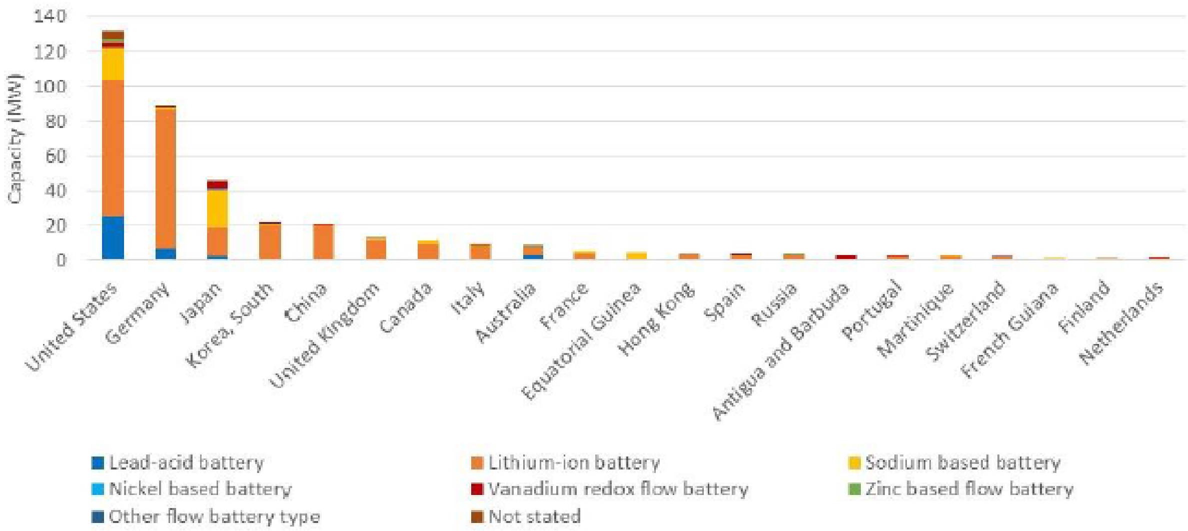

Fig. 3.8: Operational storage capacity of distribution networks [8]

3.3. Regulations and Electrical Market

3.3.1. Problem statement

For this first optimization, the scenario proposed is a Spanish market in which renewable power plants and energy storage devices are totally involved in the provision of ancillary services for network stability assurance. In Europe these services are usually mandatory and remunerated, but currently they still involve mostly the participation of fuel or gas-based power plants, thanks to their key feature of providing controllable power.

Analysing the Spanish scenario, the latest “Commission Regulation (EU) 2016/31 of 14 April 2016” establishes a network code on requirement for grid connection of generators, including renewables, that have been already mentioned in the previous resolution for the provision of network ancillary services. Despite of the great support which energy storage could provide to the grid for ancillary service provision by renewable plants, there is still not a clear and common framework to promote this service. The aforementioned regulation, indeed, clearly leaves out the requirements for energy storage devices, apart from pumped-hydro installations, although energy storage is considered by the European Network of Transmission System Operators for Electricity (ENTSO-E) as generating unit while injecting power into the grid.

Red Eléctrica de España, the network operator, cannot install and operate energy storages for ancillary services, addressing the European regulations. However, there is the possibility to provide these services with storage devices rated at less than 5 MW, which permits the development of demonstration projects [17].

Among all, this work focuses the attention on primary frequency regulation, whose aim is the assurance of constant frequency value (50 Hz) for the grid stability. Generation and demand unbalance is adjusted with power reserves provided by the PV power plant equipped with energy storage system. The provision of this service is considered as an adding value for the increase of the overall income of the power plant, since this type of ancillary service is usually remunerated.

Due to the lack of information on the requirements needed for the adoption of energy storage device for frequency control in Spain, together with the current regulations, which state that primary frequency response is a mandatory, but non-remunerated service, the market chosen as base case study for the development of the project is the UK one. So, remuneration method, prices and frequency variation data are taken from the National Grid regulatory, but they are adjusted to the limits imposed by the Spanish Grid Code.

3.3.2. European grid codes regarding participation in frequency control

Fig. 3.9 depicts the principle behavior of system frequency after a sudden lack of power generation in the network (at time t_{ip}) with all power reserve levels involved.

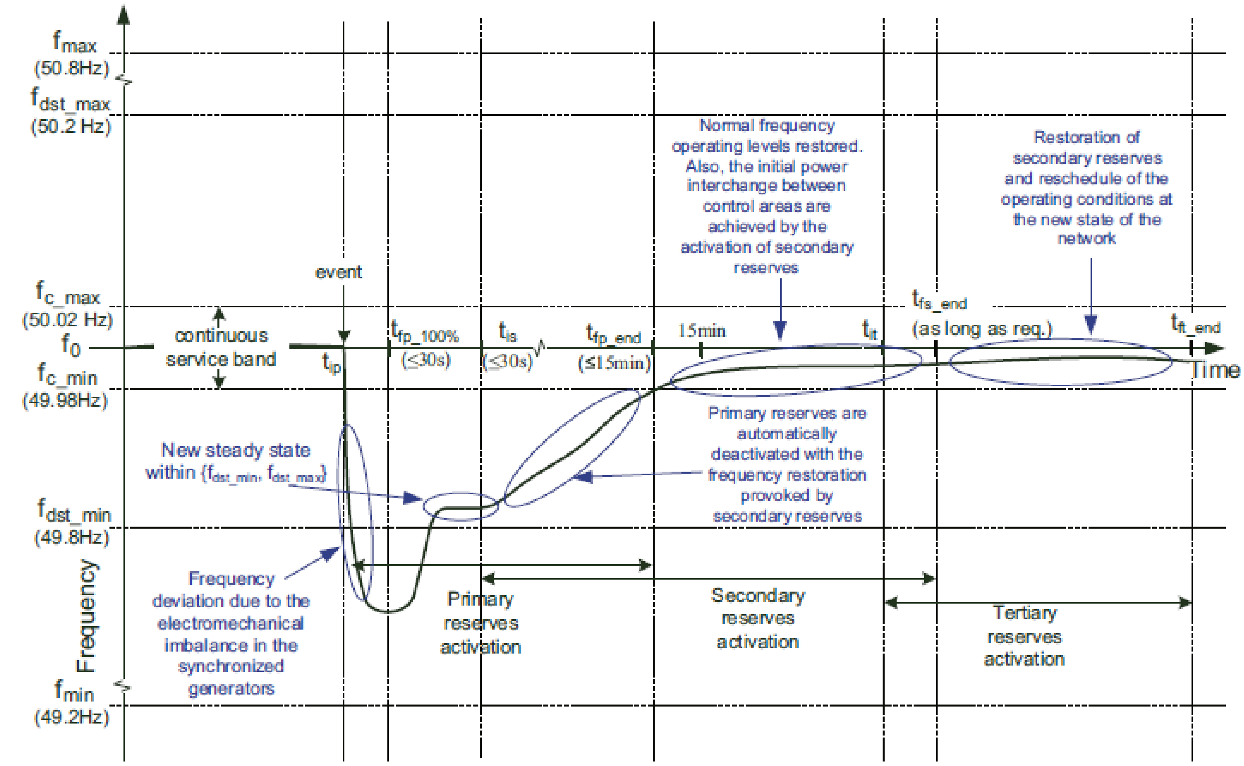

Fig. 3.9: Frequency regulation in case of low frequency event in the network [25]

First of all, the instantaneous reserves of the synchronous generating units help to recover the power balance in the network due to the stabilizing effect of the inertia. Then, as soon as a certain frequency level is reached, the primary power reserves are automatically activated and a new frequency steady state level below its rated value is achieved. The activation of secondary reserves recuperates the normal operating frequency levels and thus the deactivation of primary reserves. Secondary reserves are operated until they are fully replaced by tertiary reserves [25].

As it can be seen in Fig. 3.9, the ENTSO-E fixes some specific values of frequency and time that are summarized in Table 3.5.

Table 3.5: ENTSO-E recommendations for generating units supporting frequency control [26]

Parameters	Values	Definition
f_{min} and f_{max}	49.2 and 50.8 Hz	Minimum and maximum expected instantaneous frequency after the incident.
f_{dst_min} and f_{dst_max}	49.8 and 50.2 Hz	Minimum and maximum steady state frequency, which define the tolerance band for the quasi-steady-state system frequency recovered after the incident.
f_{c_min} and f_{c_max}	49.98 and 50.02 Hz	Limits of the frequency dead-band for the activation of primary reserve.
t_{ip}	Few seconds after detecting ± 20 mHz deviation	Maximum starting time for the activation of primary reserve.
t_{is}	≤30 s	Maximum starting time for the activation of secondary reserve.
t_{it}	Decided by the TSO	Maximum starting time for the activation of tertiary reserve.
$t_{fp_{100}\%}$	≤30 s	Maximum deployment time for 100% of total primary reserve from the event detection time.
t_{fp_end}	≥15 min	Maximum capability of actuation of primary reserve.
t_{fs_end}	As long as required	Maximum capability of actuation of secondary reserve.
t_{ft_end}	-	Maximum capability of actuation of tertiary reserve.

Apart from setting the deployment times for power reserves, regulations also specify the power reserve needs for each control area of the network, so that the stability of the system can be ensured. The required primary reserves in the synchronized European network are defined from a referent incident, which is the maximum expected power deviation between generation and consumption in the network. This referent incident of primary reserve need is set at 3000 MW, allocated throughout the network attending to the specificities of the grid of each country [25].

Furthermore, concerning primary reserve restrictions, many other features vary from one country to another; for instance, remuneration and power requirement, such as minimum rated power required to ensure this service, change according to the different Grid Codes established.

In order to harmonize the connection requirements for generating units of the European power system, the ENTSO-E presented in 2013 [26] some requirements for grid connection which are applicable to all generators. Frequency response is provided through two different types of control (Fig. 3.10):

- *Frequency sensitive mode*: the control system has the main objective of ramping the power of generating units up and down within a defined range of 1.5-10% of the nominal power, according to the frequency event occurred, under-frequency and over-frequency, respectively. In order to fulfill this requirement, the control system follows a power-frequency droop characteristic which dictates the power reserve needed for a specific value of frequency variation.

- *Limited frequency sensitive mode*: in this particular case, generating units are required to provide power reserve for under-frequency event (LFSM-U) between 49.5 and 49.8 Hz, and over-frequency event (LFSM-O) between 50.2 and 50.5 Hz, with a droop adjustable range of 2-12%. Concerning the choice of the droop and the design of the plant, a very low droop setting with more frequency sensitive responses could lead to increased maintenance costs. Taking into consideration this aspect and the fact that an over-frequency emergency situation requires active power curtailment since its reduction is the only measure against high frequency, the proposed default droop setting for Continental Europe is set at 5% [27].

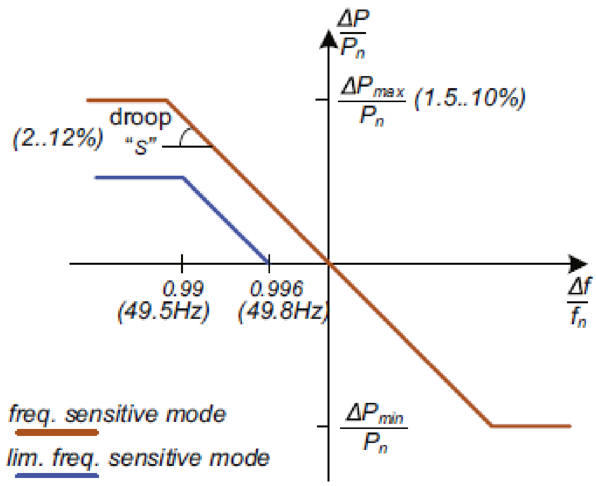

Fig. 3.10: Primary frequency control droop [25]

3.3.3. Spanish Grid Code

In case of an unbalance between generation and demand, the Procedimiento de Operación 1.5 of the System Operator [28] establishes the main requirements in order to recover the deviation occurred. This regulation dictates three different levels of frequency control:

- *Primary regulation reserve*: the power margin in which all the generators can modify their power generation automatically in two different directions in case of frequency deviation event.
- *Secondary regulation reserve*: the power deviation margin in which the Spanish peninsular system regulator can act automatically in two directions (increasing or decreasing). It is calculated as the sum, in absolute value, of the individual contributions of the all generator groups submitted for this service.
- *Tertiary regulation reserve*: composed by the maximum increasing or decreasing power variation of the all generator groups of the system, which can be activated in no more than 15 minutes and can be kept in operation until at least two consecutive hours, with the objective of reconstruct the secondary regulation reserve.

In Fig. 3.11, it is summarized the difference between this three different levels by name, features (remuneration and obligation) and entities involved. For the case of primary regulation, which is the type of service under study, the Spanish Grid Code specifies that all synchronized generators must provide primary reserves but this participation in not paid for. Just the provision of secondary and tertiary reserves is market-regulated.

Service	Type	Suppliers
Additional power reserve increase	Optional and remunerated	Thermal generating units authorized by the SO
Primary regulation	**Mandatory and non-remunerated**	**All the generating units**
Secondary regulation	Optional and remunerated	Generating units authorized and integrated in the area under regulation
Tertiary regulation	Optional and remunerated	Generators and pump units authorized by the SO

Fig. 3.11: Ancillary services description according to Red Eléctrica de España [29]

Before the 31st of December of each year, the System Operator communicates to all the producers involved in the provision of this service in the specific zones the corresponding requirements established by the ENTSO-E (before 2009 known as the Union for the Co-ordination of Transmission of Electricity, UCTE) to the Spanish peninsular electrical system for the following year.

The regulation criteria of the European interconnected system established by the ENTSO-E state that the primary regulation reserve has the main objective of stabilizing the system frequency to the quasi-steady state level within few seconds from the incident event. Furthermore, they dictate that this service has to withstand un unbalance between generation and demand for generation and demand loss or interruption of international exchanges equals to the reference incident established by the ENTSO-E, as already explained at the end of the "European grid codes regarding participation in frequency control" paragraph.

The primary regulation reserve must complete its actualization before 15 seconds from the incident time if the generation-demand unbalance is less or equal to 1500 MW. In case of higher value, the actualization of 50% of the reserve has to be produced before 15 seconds from the incident event and reach the 100% before 30 seconds. Finally, the control must be maintained during 15 minutes until the secondary reserve recovers the primary one [28].

Concerning the frequency and response time limits shown in Table 3.5, the Spanish Grid Code maintains the same values adopted by the ENTSO-E. These boundaries are taken into account in this work for the determination of the power reserves needed for frequency variations that exceed the dead-band (outside the range of 49.98 and 50.02 Hz). In other words, the primary reserve provided by the system under study follows the frequency control droop established by the ENTSO-E.

3.3.4. UK Grid Code

As previously stated, the UK frequency market model and relative requirements set by National Grid (the current System Operator) are used to develop this project.

Different types of primary frequency regulation are offered by National Grid for the power recovering in case of under or over-frequency in the network. First of all, the frequency regulation can be divided into:

- *Mandatory Frequency Response*: all large generators with rated power higher or equal than 100 MW are required to have the capability of provide automatic change in power output in response to a frequency change.
- *Commercial Frequency Response*: it is composed by two different types of response, Firm Frequency Response (FFR) and Frequency Control by Demand Managing (FCDM). FFR can offer Dynamic and Non-Dynamic Frequency Response: the first one is a continuous provided service used to manage the normal second-by-second changes on the system, while the second one is typically a discrete service triggered at a defined frequency deviation [30].

Since the project under study is characterized by a 5 MW PV power plant, the frequency response analysed referred to the Commercial Frequency Response, particularly the case of Dynamic FFR. The regulation under study is extrapolated from the FFR Interactive Guidance published in December 2017 for all the future providers which want to participate in this service from January 2018. It offers an innovative approach, allowing the participation of all generator units able to provide a minimum response of 1 MW (from a single unit or aggregated from several smaller units) [31], unlike the 10 MW requirement established by the past regulations [32]. With this new concept, the power plant under analysis is able to provide FFR and increase the net income thanks to the remuneration related to this type of service offer.

As shown in Fig. 3.12, FFR is composed by three different response speeds called:

1. *Primary response*: provided within 10 s of an event, which can be sustained for a further 20 s.
2. *Secondary response*: provided within 30 s of an event, which can be sustained for a further 30 min.
3. *High frequency response*: provided within 10 s of an event, which can be sustained indefinitely.

Primary and secondary response are employed for negative frequency deviation, while the high frequency response refers to positive frequency deviations. These frequency response capabilities are activated automatically and the generating units involved can be Balancing Mechanism (BM) and non-Balancing Mechanism (non-BM) providers. This might include generators connected to the transmission and distribution networks, storage providers and aggregated demand side response.

It is important to highlight that, according to the terminology used in this project, primary, secondary and high frequency response capability can be intended as primary reserves.

FFR product type		Response speed	Length of response
Non-Dynamic – Secondary response is the only Non-Dynamic response currently procured.		Within 30 secs	30 mins
Dynamic – A Dynamic service can provide Primary, Secondary and High response, or Primary and Secondary only or High only.	**Primary**	Response required within 2 secs, with full response by 10 secs.	20 secs
	Secondary	Within 30 secs	30 mins
	High	Within 10 secs	Indefinitely unless otherwise agreed.

Fig. 3.12: Frequency response speeds [31]

FFR is procured through a monthly electronic tender process, as shown in Fig. 3.13. Once service providers succeed in the pre-qualification assessment and sign a framework agreement, they can then tender in for a short term provision (month ahead only) or for both single and long term provision (multiple months with the maximum of 2 years). Moreover, the tender must start within 6 months of the first available tender date; for instance, tenders awarded in January must start within 6 months from 1 February.

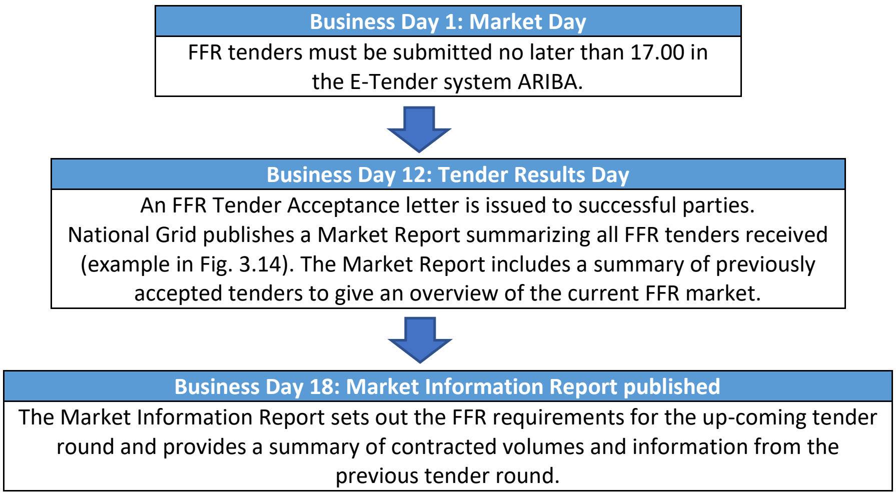

Fig. 3.13: FFR tender process [31]

	Tender ref	Provider	Unit	Start date	End date	Duration (months)	P (MW)	S (MW)	H (MW)
ACCEPTED	XX.101	1	1.01	01/10/17	31/10/17	1	40	50	40
	XX.201	2	2.01	01/10/17	31/03/18	6	25	40	0
	XX.301	3	3.01	01/10/17	31/03/18	6	25	25	25
	XX.401	4	4.01	01/01/18	30/04/18	4	10	15	0
REJECTED	XX.501	5	5.01	01/01/18	31/03/18	3	125	125	125
	XX.601	6	6.01	01/04/18	30/09/18	6	25	25	25
	XX.701	7	7.01	01/12/17	30/09/18	10	10	10	15

Fig. 3.14: Example stack of FFR tenders submitted for assessment [31]

Concerning the payment methods, most FFR tenders are made up of availability fee (£/h), which is the price per hour of service availability. However, in this project it is also considered the Response Energy Fee (£/MWh), which is based upon the actual response energy provided in the nominated window. The availability fee value has been found in the literature and it corresponds to 42 £/h, which is the price extrapolated from an historical tender data where a battery energy storage system of 2.4 MW has been nominated for FFR [33].

Concerning frequency response provided by renewables, the REF is calculated according to two possible situations (Equation 3.5 and Equation 3.6) [34]:

- Low frequency event (primary and secondary response):

$$REF_L(€/\text{MWh}) = market\ price \times 0.75$$

Equation 3.5

- High frequency event (high frequency response):

$$REF_H(€/\text{MWh}) = market\ price \times 1.25$$

Equation 3.6

In the first case, with an increase in the energy generated, a renewable generator will pick up additional Renewable Obligation Certificate (ROC) payments, which are obligations on UK electricity suppliers to source an increasing proportion of the electricity they supply from renewable sources. Where producers do not present a sufficient number of ROC to meet their obligation, they must pay a penalty [35]. In the second case, instead, with a decrease in the energy generated, a renewable generator will pick up reduced ROC payments.

3.4. Optimization problem

Let suppose that the system under study is participating in the tender process and the related battery achieves the pre-qualification assessment signing the framework agreement. The installation owner tenders in for a long-term period, providing the primary reserve service as long as the battery lifetime.

The optimization problem consists in the determination of the optimal battery size capacity and power, which enables the maximization of the power plant income. In the next paragraphs, the calculation performed to achieve it is explained in details, together with the main parameters involved in the process.

3.4.1. Objective function

The net income for the PV power plant operator, *J*, is a function of the energy sold as wholesale electricity, the costs of the storage system employed and the income from provision of frequency response. This income is represented over a period determined by the expected life span of the storage unit.

- Wholesale electricity sold at time t, in €, is given by (Equation 3.7):

$$I_{m,t} = \lambda_{m,t}\theta_t$$

Equation 3.7

where:

  - θ_t is the energy sold to the grid under regular market conditions, in MWh at the market price;
  - $\lambda_{m,t}$ is the market price, in €/MWh.

- The total cost of the energy storage system over the whole time period considered is composed of the capital and operating costs, Equation 3.8 and Equation 3.9:

$$C_s = \lambda_{pwr}S_{pwr} + \lambda_{cap}S_{cap}$$

Equation 3.8

$$C_{deg} = (\varepsilon_{lc,t} + S_{fr,t}^{-} + S_{fr,t}^{+} + S_{loss,t}) \cdot \lambda_{deg}$$

Equation 3.9

where:

  - λ_{pwr} is the power specific storage capital cost in €/MW;
  - λ_{cap} is the energy specific capital cost of storage in €/MWh;
  - S_{pwr} is the power capacity of the storage device, in MW;
  - S_{cap} is the energy capacity of the storage device, in MWh;
  - $\varepsilon_{lc,t}$ is the energy sent to the energy storage system to cover losses during time t, in MWh;
  - $S_{fr,t}^{-}$ is the energy discharged from the storage system when there is a high frequency event, in MWh;
  - $S_{fr,t}^{+}$ is the energy absorbed when a high frequency event occurs, in MWh;
  - $S_{loss,t}$ is the loss from the energy storage system in each time step as a result of leakage of charge in MWh;
  - λ_{deg} is the cost of degradation in €/MWh, obtained as expressed by Equation 3.10:

$$\lambda_{deg} = \lambda_{cap}/N_c$$

Equation 3.10

where:

- N_c is the number of cycles taken at a selected depth of discharge.

- The incomes from frequency regulation are split between responses given in the events of low and high system frequencies. Each situation requires the PV power plant equipped with the energy storage system to increase or decrease its total output.
  The income from an increase in output, I_{fr}^{+}, in €, is given by Equation 3.11:

$$I_{fr,t}^{+} = \lambda_{fr,t}^{+} \cdot \varepsilon_{fr,t}$$

Equation 3.11

where:

- $\varepsilon_{fr,t}$ is the energy provided by the system for frequency response, in MWh, within the period t;
- $\lambda_{fr,t}^{+}$ is the market price for this reserve in €/MWh.

Similarly, the income for a reduction in output for a high frequency response, I_{fr}^{-}, is defined as expressed in Equation 3.12:

$$I_{fr,t}^{-} = \lambda_{fr,t}^{-} \cdot \varepsilon_{fr,t}$$

Equation 3.12

where:

- $\lambda_{fr,t}^{-}$ is the market price for this reduction in output in €/MWh.

The total income from provision of energy for frequency regulation, I_{fr}, in €, is indicated in Equation 3.13:

$$I_{fr,t} = u_t \cdot I_{fr,t}^{+} + (1 - u_t) \cdot I_{fr,t}^{-}$$

Equation 3.13

where:

- u_t is a parameter which is equal to 1 when the frequency response required is positive, so in case of low frequency event, and 0 in the contrary case.

Finally, the objective function is defined as shown in Equation 3.14:

$$J = -C_s + \frac{365Y}{D} \sum_{t=t_0}^{N_s} \left[I_{m,t} + I_{fr,t} - C_{deg,t} \right] + \lambda_{av} \times S_{pwr}$$

Equation 3.14

This term represents the total income of the PV power plant with integrated energy storage system where:

- Y is the expected storage lifetime, in years;
- D is the number of days that the sample data covers;
- t represents the time period, expressed in seconds;
- N_s is the total number of time intervals in the data, which represents the maximum time period analysed.

3.4.2. Constraints

Constrains are collected into three main categories:

1. Global balances: equations that characterise the general energy balances of the PV power plant and link energy fluctuations from the energy storage system and PV panels.
2. PV panel balances: specific constrains which control the operation of the PV panels while providing power reserves for frequency regulation.
3. Energy storage system balances: composed by all the constrains which manage the battery charge and its response to changes in frequency.

Global balances

The following set of equations represents restrictions between the operation of the energy storage system and the PV power plant in response to frequency changes and the regular market.

- *Grid load balance*: energy sold to the grid for the participation in the electrical market; it is given by Equation 3.15:

$$\theta_t = W_{gen,t} - \varepsilon_{lc,t}/\eta^+$$

Equation 3.15

  where:
  - $W_{gen,t}$ is the PV panel generation in MWh;
  - η^+ is the charging efficiency of the battery.
- *Frequency response balance*: energy exchanged to provide frequency response services; it can be determined as explained in Equation 3.16:

$$\varepsilon_{fr,t} = W_{fr,t}^- + S_{fr,t}^- \cdot \eta^- - W_{fr,t}^+ - S_{fr,t}^+/\eta^+$$

Equation 3.16

  where:
  - $W_{fr,t}^-$ and $W_{fr,t}^+$ are the contribution from the PV panel, in MWh, when the network frequency decreases and increases, respectively;
  - η^- is the discharge efficiency of the battery.

  The PV panel contributes in the frequency reserve provision in two different ways, depending on the occurrence of a high or low frequency event in the electricity network. In case of over frequency, the inverter is able to adjust the power output according to the DC voltage (variation in the index modulation): reducing or increasing the voltage, automatically the output power is reduced. In Fig. 3.15, it is possible to observe the Safe Operation Area (SOA) of the PV panel, limited by the available maximum power of the inverter and the minimum and maximum DC voltage values. For a low frequency event, instead, a PV power plant without energy storage must work below its Maximum Power Point (MPP), in order to be able to increase the output power while needed.

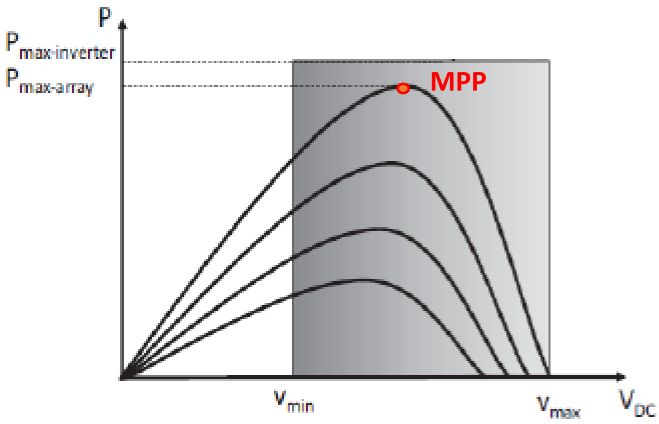

Fig. 3.15: Safe Operating Area of the PV panel for frequency response [36]

- *Appropriate reserve level*: this inequality ensures that there is always a level of reserve in the PV power plant system to respond to a maximum change in network frequency, established by the SO. The constrain is defined as to always comply with technical requirements at all times, as indicated in Equation 3.17:

$$S_{cu,t} + W_{res,t} + W_{fr,t}^{-} - W_{fr,t}^{+} \geq E_{fr,t}^{max}$$

Equation 3.17

where:

- $W_{res,t}$ is the reserve kept by the PV panels, in MWh for `purposes of allowing variation in load;
- $E_{fr,t}^{max}$ is the equivalent energy requested, in MWh, if the change in frequency equated to the maximum required. This ensures that between the charge in the battery, the reserve of the PV panels and the frequency response provided by the PV panels, there is always sufficient capacity to provide response to the worst case frequency deviation.
- $S_{cu,t}$ is the usable charge, in MWh, in the battery at time *t* and it is calculated through two inequalities, as expressed in Equation 3.18 and Equation 3.19:

$$S_{cu,t} \leq S_{pwr} \cdot T_s/60$$

Equation 3.18

$$S_{cu,t} \cdot T_{sus}/T_s \leq S_{c,t}$$

Equation 3.19

where:

- T_s is the length of the sample time of the input data in minutes;
- $S_{c,t}$ is the charge held in the storage system at time *t* in MWh;
- T_{sus} is the maximum time response in minutes.

The first inequality ensures that the usable energy in a time period can not be greater than that which the power of storage unit allows, while the second one specifies that there must be enough charge available to sustain a response for up to T_{sus}.

- *Full response provision*: Equation 3.20 ensures that all energy exchanged asked for are complied with, such that a penalty is not incurred:

$$\varepsilon_{fr,t} - E_{fr,t} = 0$$

Equation 3.20

PV panel balances

In this section, restrictions on the PV panel panels operation, including responses to frequency regulation and electricity market provision are analysed.

- *PV generation balance*: relationship between the different elements that affect the amount of generation sold in the grid in the electricity market, $W_{gen,t}$, as indicated in Equation 3.21:

$$W_{gen,t} = E_{max,t} - W_{res,t} - W_{fr,t}^{-}$$

Equation 3.21

where:

  - $E_{max,t}$ is the maximum electrical energy available that the PV panels could produce during time *t*, given in MWh.

- *Reserve energy balance*: it ensures that a reserve percentage set at the beginning of the day is either maintained or used throughout the day. This issue represents an operational decision taken based on expectations for the provision of frequency response services and determined only when $E_{max,t} \geq 0$, since the current regulation establishes that reserve provision must be provided only when the PV power plant is in generation mode. Finally, it can be defined as expressed in Equation 3.22:

$$P_{res,1533} - P_{res,t} = P_{fr,t}$$

Equation 3.22

where:

  - $P_{res,1533}$ is the proportion of the PV power reserve with respect to the maximum energy available at time 1533, which corresponds to the first positive value of energy generated during the day. In this case, it is obtained as shown in Equation 3.23:

$$P_{res,1533} = W_{res,1533}/E_{max,1533}$$

Equation 3.23

  - $P_{res,t}$ is the proportion of PV power reserve with respect to the maximum energy available at time *t.* This is given by Equation 3.24:

$$P_{res,t} = W_{res,t}/E_{max,t}$$

Equation 3.24

- $P_{fr,t}$ is the proportion of frequency response provided by the PV panel with respect to the maximum energy available at time t, as detailed in Equation 3.25:

$$P_{fr,t} = (W_{fr,t}^{-} - W_{fr,t}^{+})/E_{max,t}$$

Equation 3.25

- *Reserve limitation*: Equation 3.26 limits the PV panels reserve as a proportion of the maximum energy available, in this case 20% of $E_{max,t}$ is considered a reasonable limit:

$$W_{res,t} \leq 0.2 \cdot E_{max,t}$$

Equation 3.26

Storage balances

Restrictions to the charge balance and operation of the energy storage system for its contribution of frequency regulation are examined.

- *Charge balance*: general balance of the charge of the battery and its energy inputs and outputs, given by Equation 3.27:

$$S_{c,t} - S_{c,t-1} = \varepsilon_{lc,t} + S_{fr,t} - S_{loss,t}$$

Equation 3.27

where:

- $S_{fr,t}$ is the net frequency response of the storage system provided at time *t* and defined as expressed in Equation 3.28 and Equation 3.29:

$$S_{c,t} \leq \alpha_H \cdot S_{cap}$$

Equation 3.28

$$S_{c,t} \geq \alpha_L \cdot S_{cap}$$

Equation 3.29

where α_H and α_L are the high and low percentage limits for the state of charge in relation to the storage capacity, S_{cap}.

- *Power limits*: they define the power of the storage unit by the maximum of the incoming and outgoing energy flows over the period of analysis through Equation 3.30 and Equation 3.31:

$$(\varepsilon_{lc,t} + S_{fr,t}^{+}) \cdot 60/T_s \leq S_{pwr}$$

Equation 3.30

$$(\varepsilon_{loss,t} + S_{fr,t}^{-}) \cdot 60/T_s \leq S_{pwr}$$

Equation 3.31

- *Storage losses*: they are taken into consideration, furthermore, loss compensation is restricted to a reasonable level by Equation 3.32 and Equation 3.33:

$$S_{loss,t} = S_{c,t} \cdot \gamma$$

Equation 3.32

$$\varepsilon_{lc,t} \leq 1.2 \cdot S_{loss,t}$$

Equation 3.33

where:

- γ is the loss percentage expected from the storage system in each time sample due to charge leakage; in other words, it is known as self-discharge.

Basic constrains

Finally, in Table 3.6, it is possible to observe the variables associated to two main constrains: non-negative values and initial values set to zero.

Table 3.6: Other constrains

Variable	Initial value set equal to zero	Non-negative value
S_{pwr}	√	X
S_{cap}	√	X
$\varepsilon_{lc,t}$	√	√
$S^{+}_{fr,t}$	√	√
$S^{-}_{fr,t}$	√	√
$W^{+}_{fr,t}$	√	√
$W^{-}_{fr,t}$	√	√
$W_{res,t}$	√	X

3.4.3. Parameters

In this section, the real data used for the implementation of the optimisation are discussed. The problem is characterised by some parameters, already presented in the previous paragraphs, whose values are selected as convenience and found in literature, as shown in Table 3.7.

Table 3.7: Parameters

Parameter	Unit	Value
N_s	-	5760
λ_{pwr}	€/kW	160
λ_{cap}	€/kWh	338
α_L	-	0.1
α_H	-	1
η^{-}	-	0.92
η^{+}	-	0.92
Y	years	15
D	day	1
T_s	minutes	0.25
γ	-	0.05
λ_{deg}	€/kWh	0.112

N_s represents the number of samples: this value is determined through Equation 3.34 considering one day (*D*) and calculating how many data are collected for measurements taken every 15 seconds (T_s).

$$N_s = 1 \text{ day} \cdot \frac{24 \text{ h}}{1 \text{ day}} \cdot \frac{60 \text{ min}}{1 \text{ h}} \cdot \frac{60\ s}{1 \text{ min}} \cdot \frac{1}{15 \text{ s}} = 5760$$

Equation 3.34

The prices for battery capacity and power converter (λ_{cap} and λ_{pwr}) are extrapolated from [22] and from a reference project data, where Lithium-ion battery NMC type and related inverter prices have been provided by the manufacturer.

Upper and lower sate of charge limits (α_L and α_H) are taken as reference from [9].

For the degradation cost (λ_{deg}) determination, Equation 3.10 is applied, where the battery number of cycles (N_c) is taken from Table 3.4 at an assumed DoD, resulting in:

$$\lambda_{deg} = \frac{\lambda_{cap}}{N_c} = \frac{338}{3000} = 0.112 \text{ €/kWh}$$

Finally, battery lifetime data is taken from [37], while self-discharge (γ) value is shown in Table 3.4.

Apart from the parameters shown in Table 3.7, GAMS presents other 5 main parameters, which are described as follows:

- *Maximum generation*, $E_{max,t}$ (MWh): it is the energy generated by the PV power plant according to the availability of the solar radiation in a determined period of time. Data are collected in a day for measurements taken each 15 seconds, as already described in the **PV power plant** chapter.
- *Market price*, $\lambda_{m,t}$ (€/MWh): it is the market marginal price of the Spanish electricity market. Data are taken from the Operador del Mercado Ibérico de Electricidad (OMIE) website [38]. It represents the Market Operator in the Iberian Peninsula, managing the electricity market of Portugal and Spain. In this case, electricity prices are available for each hour of the day, so the same data is maintained for all the samples contained in one hour, accounting finally for 5760 values in the selected day of 19th March 2018 (Fig. 3.16).

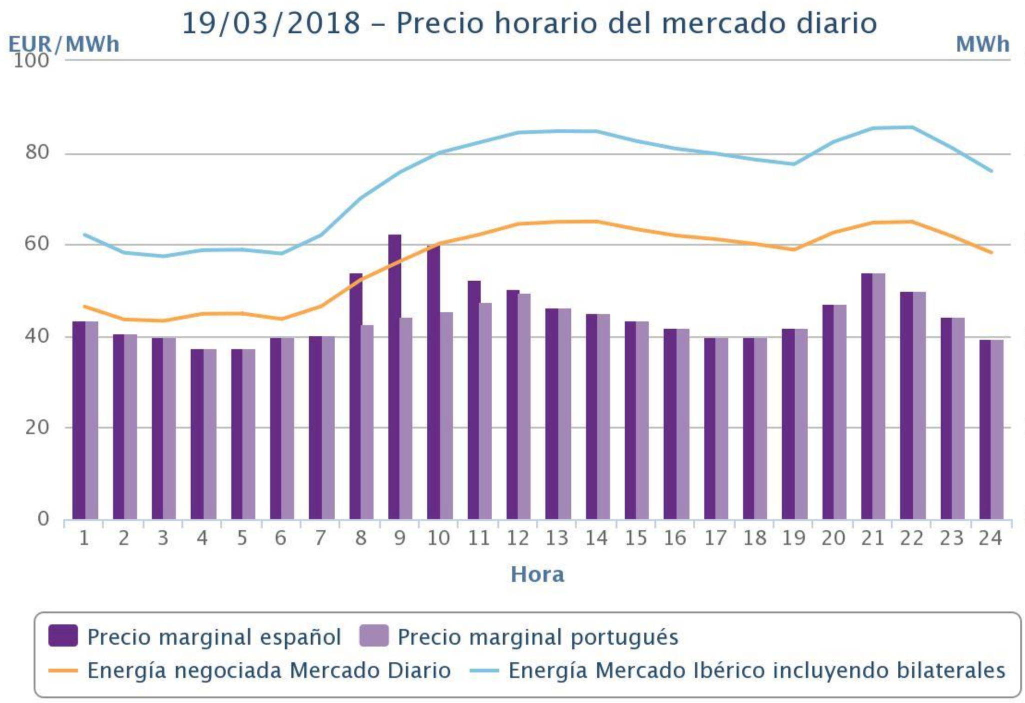

Fig. 3.16: Market marginal price in €/MWh *(*λ_m*) for 19th March 2018 [38]*

- *Requested frequency energy response*, $E_{ft,t}$ (MWh): it represents the energy provided by the power plant in the event $\pm 0.25\ Hz$ frequency variation in the network, producing or curtailing a determined amount of energy according to the deviation occurred. First of all, it is necessary to extrapolate frequency deviations data for each 15 seconds in a day: measurements are provided by the UK SO in its website every second, so they need to be adapted to form only 5760 samples [39], as shown in Fig. 3.17. Once determined the frequency variation (see ANNEX for more details), it is necessary to calculate the amount of energy needed for each frequency deviation. This determination can be managed by building the frequency control droop established by the ENTSO-E, following limits and constrains instituted by the Spanish Grid Code. It is important to highlight that, according to the current regulation, reserve provision is allowed only when the power plant is generating electricity.

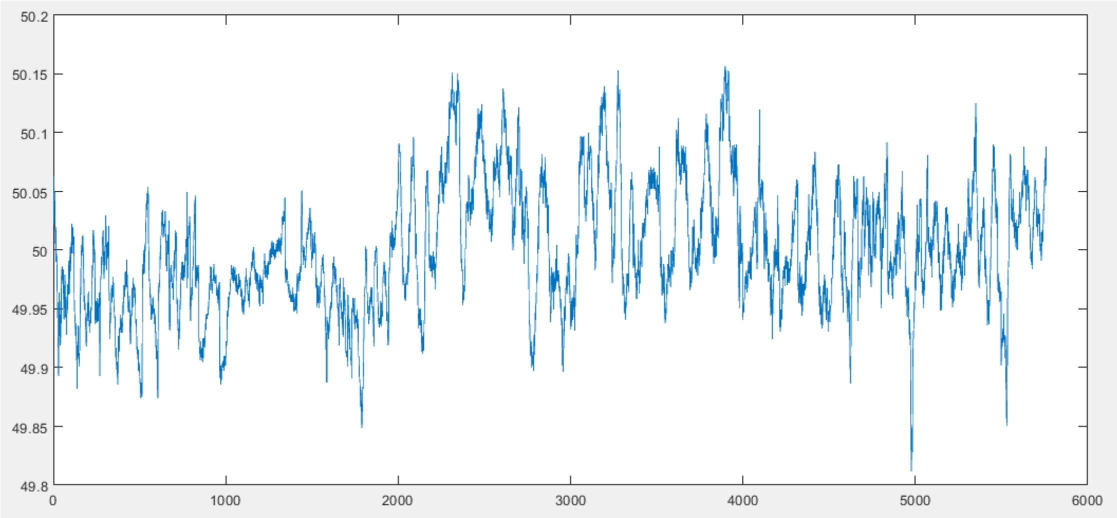

Fig. 3.17: Frequency variation data

Error! Reference source not found. describes the methodology implemented, where:

- P_{ref} is the actual active power output of the power plant;
- ΔP is the change in active power output from the power generating module;
- f_{ref} is the nominal frequency in the network (50 Hz);
- Δf is the frequency deviation in the network;
- s is the slope, which in this case is set at 5% (as stated by [27]), but it is generally calculated through Equation 3.35 [40]:

$$s\ [\%] = 100 \cdot \frac{\Delta f}{f_{ref}} \cdot \frac{P_{ref}}{\Delta P}$$

Equation 3.35

Moreover, constrains indicated in Table 3.8 have to be followed:

Table 3.8: Frequency regulation constrains

Δf	$\Delta P / P_{ref}$	Comments
≤ -0.25	0.1	In a range between 1.5% and 10%, the worst case is selected: 10% of the available active power is required for power reserve provision
between -0.25 and -0.02	$0.5 \cdot \Delta f$	-
between -0.02 and 0.02	0	Inside the dead band there is no reserve provision
between 0.02 and 0.25	$0.5 \cdot \Delta f$	-
≥ 0.25	-0.1	10% of the available active power is curtailed for frequency regulation

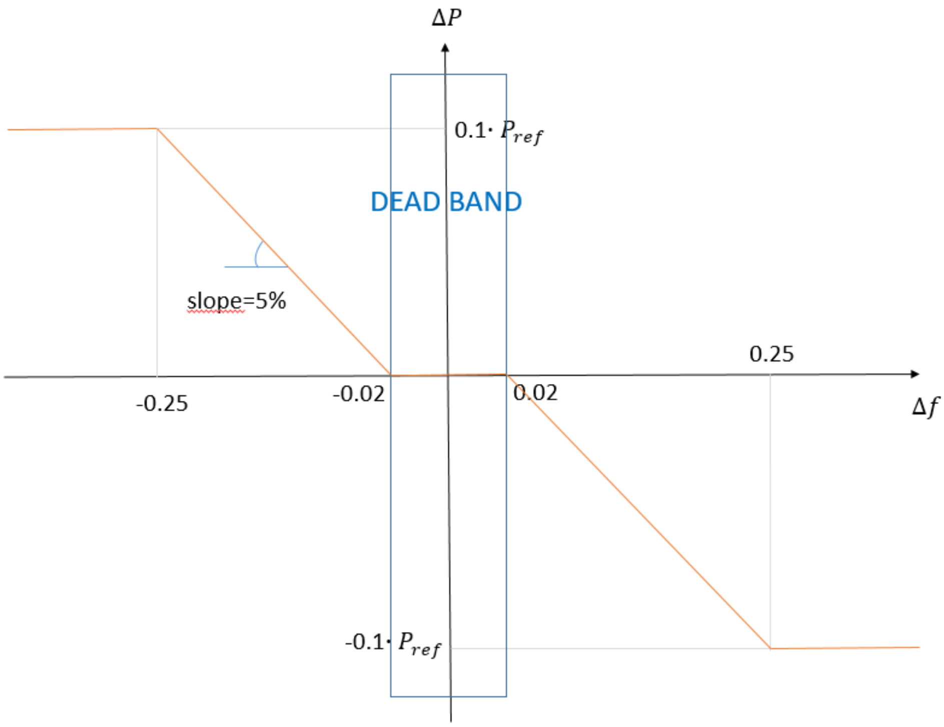

Fig. 3.18: Frequency control droop ±0.25 Hz variation

Once the values of $\Delta P/P_{ref}$ are calculated, the reserve provision in power is determined through Equation 3.36:

$$\Delta P = (\Delta P/P_{ref}) \cdot P_{ref}$$

Equation 3.36

In this particular case, since the PV power plant generation has been obtained directly in energy, the methodology implemented is followed using energy, instead of power.

- *Frequency response energy at maximum change*, $E_{fr,t}^{max}$ (MWh): the current regulation [40] does not fix a value for maximum frequency change, allowing to select the most convenient one according to the optimization performed. In this case the energy requested corresponds to a maximum variation of -0.5 Hz from the nominal value: the case of under-frequency of 49.5 Hz in the electricity network is examined. Although in the frequency data taken from National Grid there are no results accounting for such a deviation in the electricity network, this worst case is ideally taken into account to ensure that the system is able to provide a big amount of reserve in extreme network conditions. The methodology followed is the same used for the previous parameter, however the frequency control droop limits and features are different, as shown in Fig. 3.19. Moreover, only the case of under-frequency is analysed, which limits the operation of the droop only on the first quarter (top left side).

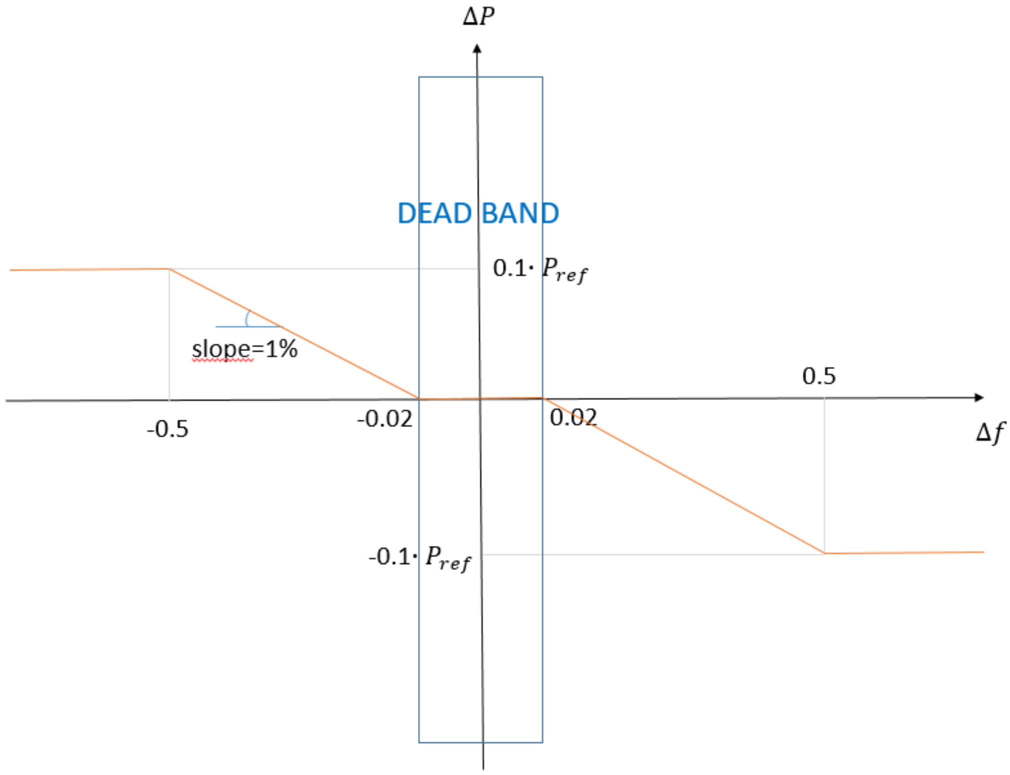

Fig. 3.19: Frequency control droop -0.5 Hz *variation*

- *Utilised frequency response price*, $\lambda_{fr,t}$ (€/MWh): it represents the payment offered for the provision of primary reserve. As previously mentioned, since in Spain there is no remuneration for this type of service, prices are extracted from the UK market. The REF price ($\lambda_{REF,t}$), is already calculated in €/MWh through the formula explained in the UK Grid Code section for the two different situations: over or under frequency event in the network. Apart from this remuneration, the availability fee has been previously mentioned as a payment provided by National Grid making primary reserve provision available. This parameter is not included in the optimization process itself for the determination of the best battery size, but it has to be taken into account once obtained the value of the objective function (*J*), which determines the total income of the plant ($\lambda_{tot} = J + \lambda_{av}$). Taking into consideration that the primary reserve provision can be possible only when the power plant is in operation, according to the annual hours of sun in Spain, the energy storage system is offering the service for 26% of the total annual hours [41] with a offered band of 10% of the nominal PV plant power. Finally, the availability price can be calculated as expressed in Equation 3.37:

$$\lambda_{av} = 42\frac{£}{\mathrm{h}} \times \frac{1.14\ €}{1\ £} \times 8760\ \frac{\mathrm{h}}{\mathrm{years}} \times 0.26 \times \frac{15\ \mathrm{years}}{2.4\ \mathrm{MW}} \times 0.1 \times 5\ \mathrm{MW} = 340780\ €$$

Equation 3.37

4. FORECASTING ERROR OPTIMIZATION MODELLING

The electrical energy producer has to be capable of predict the PV plant generation as close as possible to the real effective production, since, in Spain, forecasting errors are economically penalized. Especially for the renewable sector, this concept represents a very important issue, since, due to the intermittence nature of the resource, the prediction estimation results even more difficult. As previously stated, the implementation of an energy storage system, a battery device in this case, improves the reduction of the errors prediction, thus decreasing the costs related to the penalization imposed by the Spanish electrical market. The battery storage system, indeed, is able to provide that energy which the PV power plant is not capable of generate in case of climate changes and therefore deviations in the production forecast.

This second optimization keeps the main objective of maximising the power plant income, employing the storage system for primary frequency response, as well as for forecasting error decrease. The main features that have to be taken into account are indicated in Fig. 4.1, which shows the methodology implemented for the optimization process.

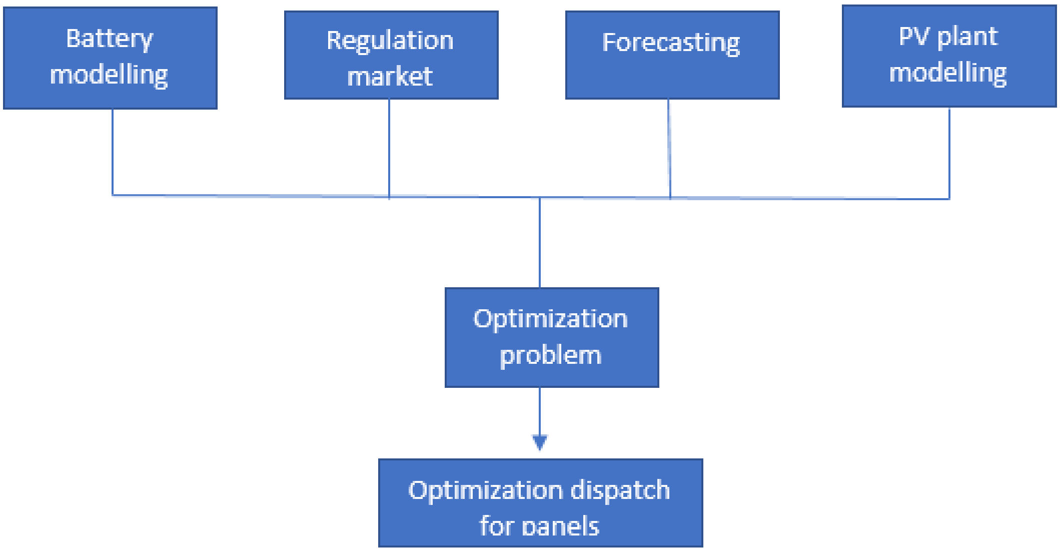

Fig. 4.1: Methodology implemented

4.1. Regulations and electrical market

The Spanish electricity market consists in a de-regulated operational market where generation and demand exchange electric energy in different time horizons and no information pertaining to producers and consumers is transferred to the market operator (MO).

According to the article 2 of the *Real Decreto 2019/1997*, of the 26th December, the electric energy production market is structured in forward markets, day-ahead market, intraday markets, nonorganised markets and system balancing markets [42]. Fig. 4.2 (red shapes) indicates the two markets under analysis: day-ahead and diversions ones.

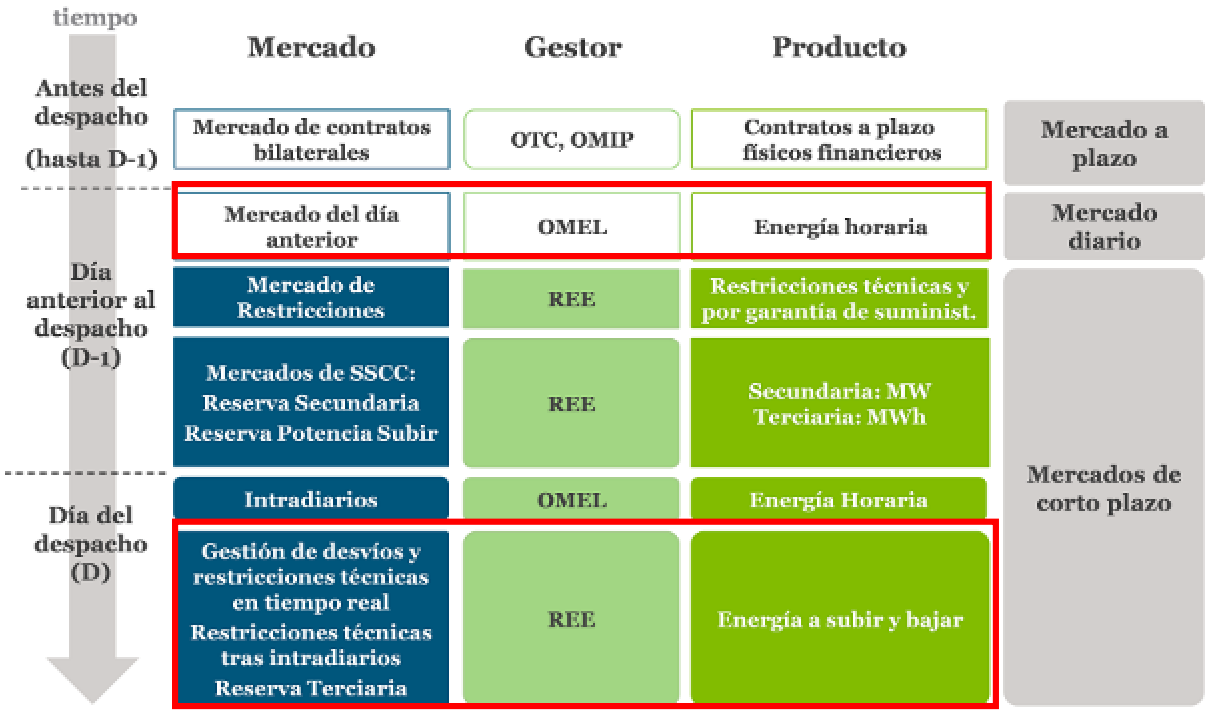

Fig. 4.2: Markets under analysis (red) [43]

4.1.1. Day-ahead market

The day-ahead market (DM) has the main objective of carrying out the energy transitions for the next day through the presentation of selling offers and purchase of electric energy made by the market agents starting at 12.00 pm.

First of all, in order to sell their energy, producers have to agree with the *Reglas de Funcionamiento del Mercado de Producción de la Energía Eléctrica* through a subscription of the corresponding *Agreement Contract*. The offers of the generators are presented to the MO (OMIE in Spain) as a daily programming schedule corresponding to the day after the deadline date for the reception of bids for the session, and comprising twenty-four consecutive programming hours [44]. Buyers, composed by retailers, resellers and direct consumers, also present their offers in the DM, known as bids. The MO has now to determine the market clearing prices through the market clearing procedure execution. It is known as pool, where trading between producers and demand is developed in a centralised manner. The market equilibrium is determined in a systematic way for each hour following the methodology shown in Fig. 4.3:

- Generation curve: suppliers submit offers (monotonically increasing) to supply a certain amount of electrical energy at a determined price and these are ranked in order of increasing price;
- Demand curve: retailers/consumers submit bids (monotonically decreasing) specifying quantity and price and ranking these offers in decreasing order of price.

The intersection between generation and demand curves corresponds to the marginal market price. Generators with offers at a price lower than or equal to such price are accepted, while concerning the demand, consumers with bids at a price greater or equal to such price are accepted.

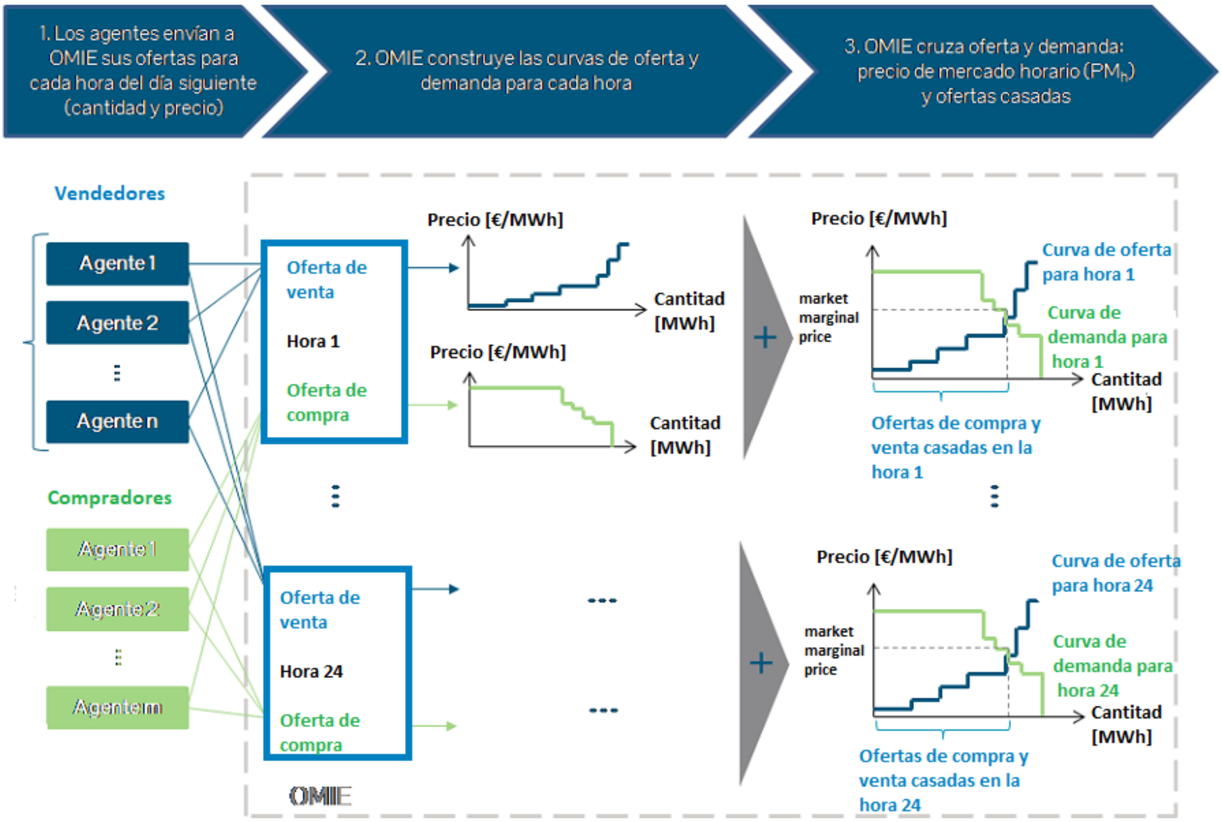

Fig. 4.3: DM operation scheme of OMIE [43]

4.1.2. Diversions management market

“Generation-consumption diversions are originated by the difference between real production and forecasted generation, demand variation of the system and/or mandatory changes of production schedules, as well as the difference between the expected production in the Spanish electric peninsular system and the programmed demand after the results of the different sessions of the intraday market (IM). The diversions between generation and consumption occurred due to unavailability and/or deviations of the generating unit respect to the market programme and/or changes in demand forecast and/or expected production deliveries of wind and solar energy can be solved through the implementation of the diversions management (*gestión de desvíos*) mechanism.

The solutions are provided for deviations which can appear after each closure of the IM session, covering all the time horizon at maximum until the beginning of the next IM session" [45].

In other words, and taking into account a PV generation, the producer participates as generator in the day-ahead market, selling the energy expected. In the case of a deviation from the forecast, he/she can adjust the prevision in the IM (shorter time horizon means smaller forecasting errors), avoiding the risk of penalizations imposed by the SO.

During the normal operation, producers communicate to the SO the deviation forecasts generated by different causes, while the SO reports the forecast variations of renewable power plants. In the case of deviations higher than 300 MWh [46], the diversions management called by the SO is taking place. This market consists in asking generators to offer energy in the opposite trend of the system variations, according to the type of deviation and the system necessity. The diversion can be classified as increasing (*a subir*), when the producer generates more than expected, and decreasing (*a bajar*), when the producer incurs in production deficit. According to the system necessity, the deviation can be favourable (green) or opposing (pink), as shown in Fig. 4.4; for the four different configurations, the producer is facing the following situations and related diversion prices (Fig. 4.5):

a) The production is higher than the expectation and the system needs more energy → favourable deviation.
   The surplus of energy is sold at the PMD, thus counting as income for the producer.
b) The producer generates less energy than expected and the system needs more energy → opposing. The generator incurs in penalizations, since he/she has to pay the energy deviation at the decreasing diversion price (*precio desviamiento a bajar*, PDSVB).
c) The production is lower than the forecasted and the system demand decreases → favourable. The energy generated is sold at the marginal market price (*precio mercado diario*, PMD).
d) The generation is higher than forecasted and the demand is lower → opposing, the surplus of energy is sold at the increasing diversion price (*precio desviamiento a subir*, PDSVS). Actually, this scenario is not considered as a penalization since the deviation value is positive and it represents an income. However, the producer gains less than if he would have predicted the deviation, as the PDSVS is always lower than the PMD.

These prices are established by the system operator and relative historical data are available in Red Electrica de España website [47].

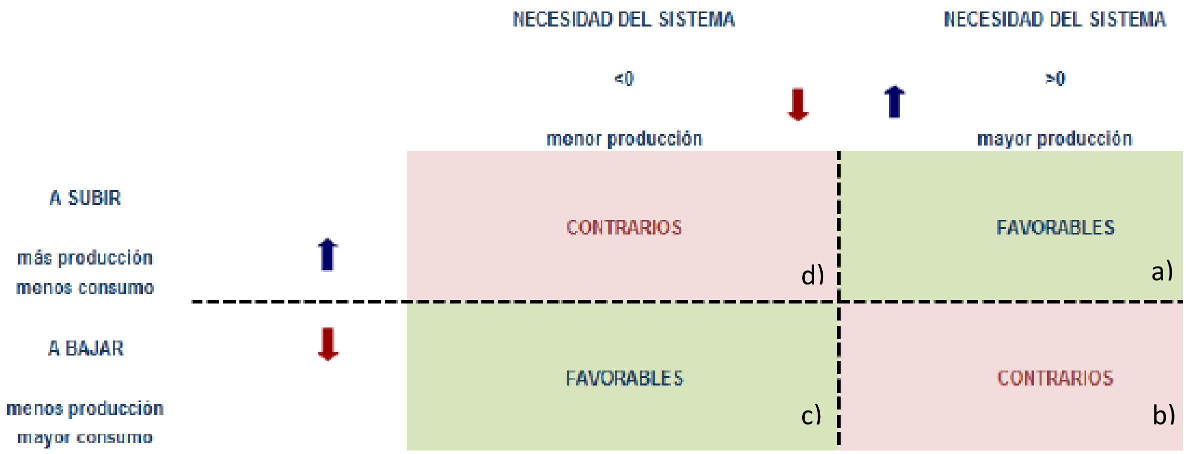

Fig. 4.4: Diversions [48]

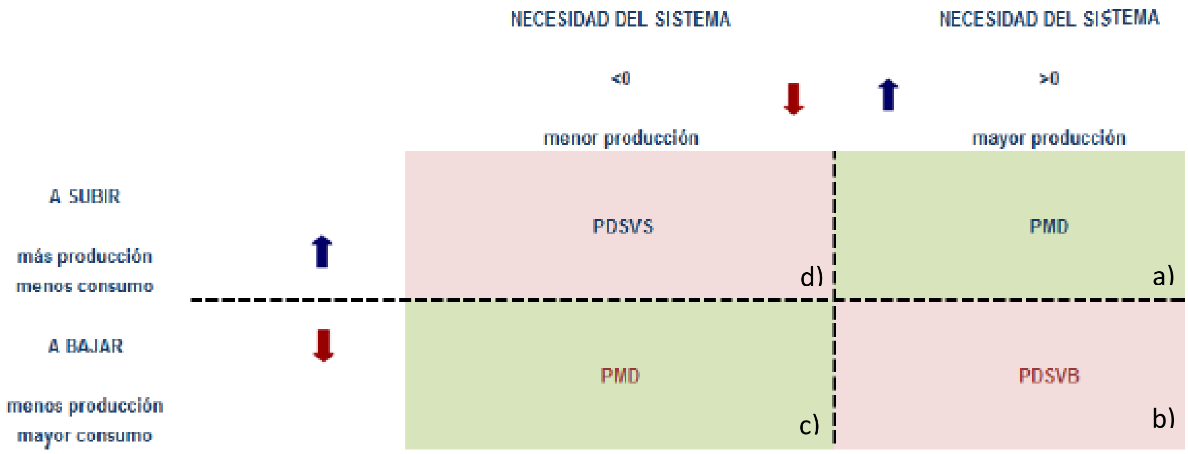

Fig. 4.5: Diversion prices [48]

As previously stated, if on one hand, the PDSVB is always higher than the PMD, on the other hand, the PDSVS is always lower than the PMD. PDSVB, indeed, is the loss for having paid a not produced energy in the market, which has generated an additional payment for the SO. As a consequence, the producer has to pay the missing energy at the PDSVB. PDSVS, instead, is the "loss" for selling an energy which could have been sold in the market at higher price.

Taking into consideration historical data, Red Electrica de España furnishes a complete report concerning ancillary services and in particular the case of diversions management. In its document, a summary of the diversions occurred during each year is explained, with fundamental details about prices and occurrence. In Fig. 4.6, it is possible to observe the hours of increasing and decreasing diversions occurred in Spain for each month of the year 2017.

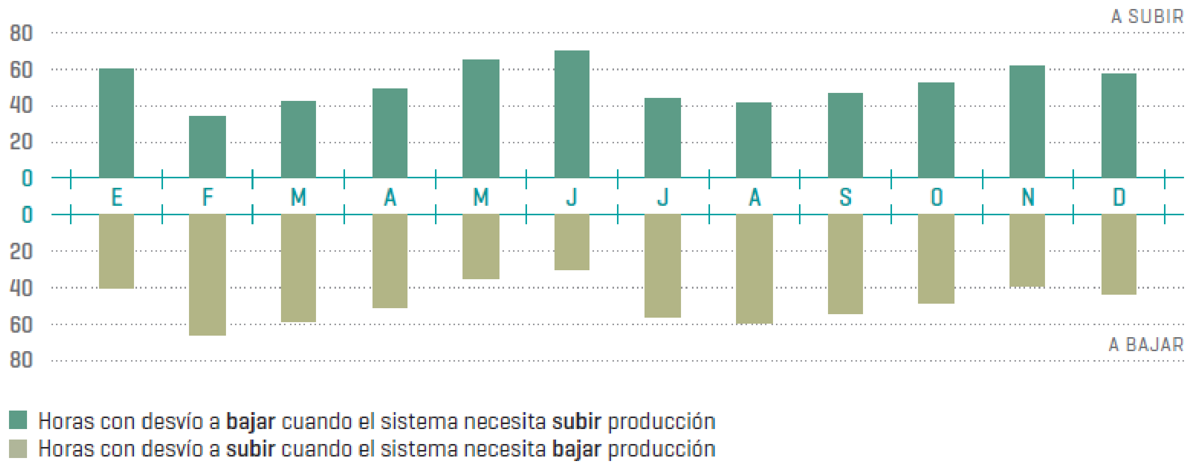

Fig. 4.6: Hours of diversion in 2017 [49]

As this work performs the forecasting errors penalizations analysis only referring to the DM, the deviation management market is taken into account just for the deviation prices calculation. The system under analysis is, indeed, composed by a PV power plant equipped with batteries, which have the main objective of adjust the forecasting errors in that case in which the surplus of energy is not totally sold in the DM market and so it is stored in the device, or in the case where the production is lower than the expectations and the missing energy is provided by the batteries as much as they can, without involving the deviations management market. So, the power plant is not taking part in this type of market, but it consists in a self-adjustment installation with the main objective of increasing the income related to its participation in the day-ahead electricity market.

4.2. Forecasting error

As previously explained, in Spain the rules of the electricity market force the PV electricity producer to provide to the market operator the energy schedule that will be fed into the grid for each hour of the future market session. Anticipating cases of shortage or abundance of solar power, the producer avoids penalties established by the SO when schedule is not strictly met. However, the intermittency of the solar energy resource makes forecasting a difficult issue, provoking unexpected unbalance between generation and demand, thus decreasing the power plant income, since the higher forecasting error there is, greater the penalization will be. For this reason, accurate solar forecasting systems are needed to provide in-advance estimations of the hourly energy generation for a forecasting horizon of nearly two days, in order to eliminate the impact of output uncertainty, improve system stability and increase PV penetration in the grid reducing ancillary services costs.

As shown in Fig. 4.7, forecasting methods can be classified depending on [50]:

- Resolution method: it refers to the nature of the input data, which can be:
    - Physical: it consists in the use of variables that characterise the area under study. Fig. 4.8 shows the main inputs used for this type of method, classified by importance distinguishing between winter and summer. The time horizon with an acceptable error

is around 10 hours, which means that for the DM participation (36 hours), the physical method has to be integrated with data related to other meteorological models, adjusting the values for large time horizon.

- Statistical: it extrapolates future values of a specific variable through the analysis of the values that the variable assumed in the past. This is called time-series statistical method and it covers predictions within 40 hours. Future values can be obtained through two different methods:
    - Persistency: it corresponds to the simplest method for PV energy forecasting. It is characterised by high prediction accuracy in the case of short-time horizon (1 hour).
    - Mathematic: it reveals optimal accuracy for time-horizon larger than 3 hours. Some of the main mathematical methods currently under exploitation are the Autoregressive Integrated Moving Average (ARIMA) model, the Box-Jenkins methodology, as well as the Artificial Neural Network (ANN) [51].

- Time horizon: it consists in the time interval between the moment in which the forecasting is made and the future instant for which the prevision is made. It can be classified in:
    - Short term prediction: the time horizon does not overcome 10 hours. This method is used by the producer for the IM participation and by the SO to ensure stability between generation and demand through adjustment mechanisms.
    - Medium term prediction: the time horizon is included between 10 and 72 hours. This method is used for the DM participation; since the producer has to submit the offers at 12pm of the day before the supply, the time horizon consists in around 36 hours.
    - Long term prediction: the time horizon is fixed for intervals greater than 3 days. This method represents the most inaccurate, since the greater the time horizon is, the greater the forecasting errors will be. It does not play any role in the electricity market, however, it can be used for detecting irradiance scarcity periods in which maintenance can be scheduled.

Fig. 4.7: Forecasting methods classification [50]

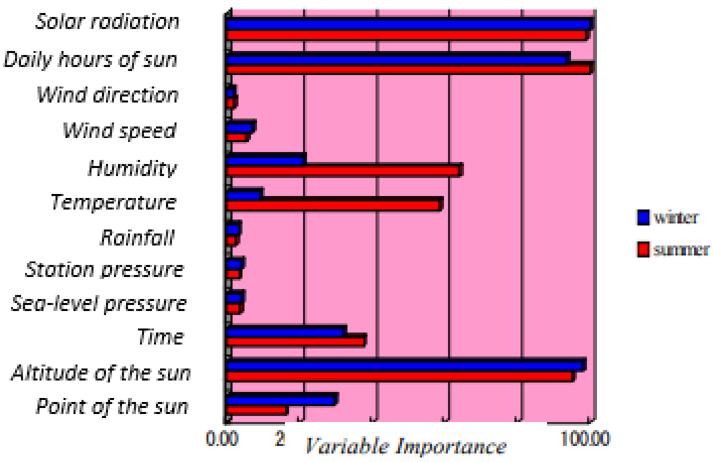

Fig. 4.8: Input data for physical forecasting model in PV plants [52]

In the current project, previsions are determined through a probabilistic method. This is because statistical method can not be optimally applied, due to scarcity of data from previous years which would cause huge forecasting errors. International Energy Agency (IEA) examines the probabilistic approach in its "Solar Resource Knowledge Management", analysing root mean square error (RMSE), mean absolute error (MAE) and mean bias error (bias), defined through Equation 4.1, Equation 4.2 and Equation 4.3:

$$RMSE = \sqrt{\sum_{i=1}^{n} \frac{(x_{real,i} - x_{for,i})^2}{n}}$$

Equation 4.1

$$MBE = Bias = \sum_{i=1}^{n} \frac{(x_{real,i} - x_{for,i})}{n}$$

Equation 4.2

$$MAE = \sum_{i=1}^{n} \frac{|x_{real,i} - x_{for,i}|}{n}$$

Equation 4.3

where:

- $x_{real,i}$ is the real value;
- $x_{for,i}$ is the forecasted value;
- i is the index data under analysis;
- n is the number of data samples.

RMSE gives more weight to large errors, whereas MAE reveals the average magnitude of the error and bias indicates whether there is a significant tendency to systematically over-forecast or under-forecast.

For this project, the values of error used to create the error curve are the ones related to the RMSE, which have to follow a graphical distribution as shown in Fig. 4.9. Forecasting errors, indeed, depend strongly on the time of the day and approximately follow the daily course of irradiance in the array plane. The evolution of errors with forecast horizons reflects both this daily trend as well as the decrease in forecast accuracy as forecast horizon increases.

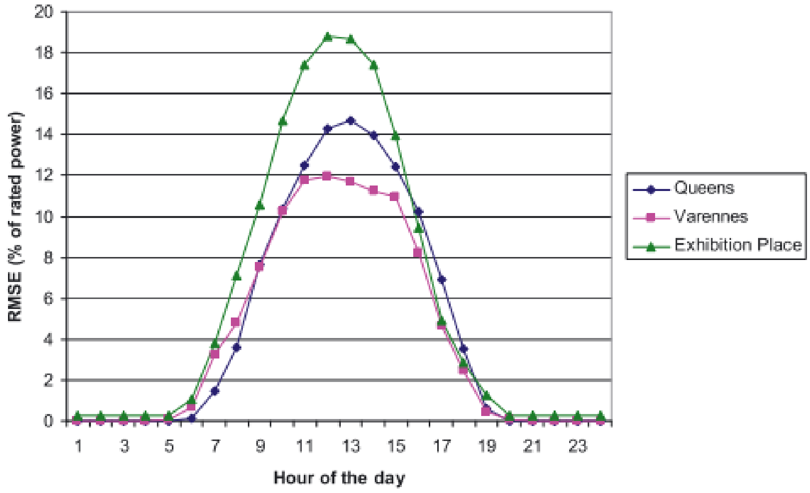

Fig. 4.9: PV forecast accuracy (RMSE) as a function of time of day [53]

4.3. Optimization problem

The optimization process is performed through GAMs software and it has the main objective of dimensioning the optimal battery size to enhance the forecasting error reduction service together with the provision of primary frequency response. The code structure used is the same analysed in the PRIMARY FREQUENCY CONTROL OPTIMIZATION MODELLING, however, new constrains, parameters and variables are added.

4.3.1. Objective function

The net income for the PV power plant operator, *J*, is represented over a period determined by the expected life span of the storage unit and it is a function of:

- the wholesale electricity sold at time *t*, $I_{m,t}$;
- the total cost of the energy storage system over the whole time period, C_s and $C_{deg,t}$;
- the incomes from frequency regulation, $I_{fr,t}$;
- the income/payment that affect the producer income related to the forecasting errors made during the DM energy scheduling , $I_{dev\ m,t}$. This variable can be positive (income) or negative (penalization), according to the system necessity; each addend of Equation 4.4 expresses one of the four possible scenarios previously explained in the **4.1.2. Diversions management market** section:

$$I_{dev\,m,t} = (\theta_{1t} - \theta_t) \cdot \lambda_t^+ \cdot A_t \cdot (1 - N_t) + (\theta_{1t} - \theta_t) \cdot \lambda_{m,t} \cdot A_t \cdot N_t + (\theta_{1t} - \theta_t) \cdot \lambda_t^- \cdot (1 - A_t) \cdot N_t + (\theta_{1t} - \theta_t) \cdot \lambda_{m,t} \cdot (1 - A_t) \cdot (1 - N_t)$$

Equation 4.4

where:

- θ_t is the forecasted energy that is programmed to be sold in the DM, in MWh; it is obtained as in the first optimization through equation $\theta_t = W_{gen,t} - \varepsilon_{lc,t}/\eta^+$);
- θ_{1t} is the effective energy generated by the power plant, which can be sold in the DM, in MWh; it is calculated expressed in Equation 4.5:

$$\theta_{t1} = \theta_t + \varepsilon\theta_t + S_{dev,t}^- \eta^- - S_{dev,t}^+ / \eta^+$$

Equation 4.5

  where:
  - $\mathcal{E}$ is the forecasting error;
  - $S_{dev,t}^-$ is the energy discharged from the batteries for forecasting errors adjustment, in MWh;
  - $S_{dev,t}^+$ is the energy absorbed by the batteries for forecasting errors adjustment, in MWh.
- λ_t^+ is the increasing deviation price (the aforementioned PDSVS), expressed in €/MWh;
- A_t is a binary data regarding the producer deviation:

$$\begin{cases} 1 \text{ increasing deviation: more generation than forecasted} \\ 0 \text{ decreasing deviation: less production than forecasted} \end{cases}$$

- N_t is a binary data concerning the system necessity:

$$\begin{cases} 1 \text{ need of more production than scheduled} \\ 0 \text{ need of less production than scheduled} \end{cases}$$

- λ_t^- is the decreasing deviation price (the aforementioned PDSVB), expressed in €/MWh.

Finally, the objective function is defined in Equation 4.6:

$$J = -C_s + \frac{365Y}{D} \sum_{t=t_0}^{N_s} \left[I_{m,t} + I_{fr,t} + I_{dev\,m,t} - C_{deg,t} \right] + \lambda_{av} \times S_{pwr}$$

Equation 4.6

4.3.2. Parameters

In this section, the real data used for the implementation of the optimisation are discussed. The problem is characterised by some parameters, already presented in the previous optimization and summarised in Table 3.7. Apart from these values, the process presents other main parameters. They are all indicated and explained in the following bulleted list:

- *Maximum generation*, $E_{max,t}$ (MWh): it is the maximum energy generated by the PV panels at time *t*;
- *Market price*, $\lambda_{m,t}$ (€/MWh): it is the price at which the energy is sold to the DM at time *t*;
- *Requested frequency energy response*, $E_{ft,t}$ (MWh): it represents the energy requested to stabilise the network frequency at time *t*;
- *Frequency response energy at maximum change*, $E_{fr,t}^{max}$ (MWh): it is the energy requested to stabilise the network frequency at time *t* in case of maximum frequency variation event;
- *Utilised frequency response price*, $\lambda_{fr,t}$ (€/MWh): it consists in the remuneration price at time *t* for providing frequency response;
- *Error*, ε: it represents the forecasting error made by the producer during the prediction of the energy scheduling that has to be sold in the DM. Starting from a pre-existent RMSE vector [10] with trend shown in Fig. 4.10 (blue line refers to the current case, DM), the error is performed through Matlab, resulting in a disturb represented graphically in Fig. 4.11. In order to obtain the real PV panel generation affected by forecasting errors, it is necessary to apply Equation 4.7:

$$x_{real,i} = x_{for,i} + \varepsilon x_{for,i}$$

Equation 4.7

where, in the current case:

- $x_{for,i} = \theta_{t,i}$, which is the producer forecasting of the energy that will be sold in the market excluding the contribution of primary reserve provision, in kWh;
- $x_{real,i} = \theta_{t1,i}$, which corresponds to the effective energy sold in the market, in kWh.

Looking at Fig. 4.12 and Fig. 4.13, it is possible to observe the difference between the producer forecasting (blue) and the real energy generated (orange). Particularly, in the second graph, it is clearly expressed the diversion from the real energy offered. During the all day, the effective energy generated, which can be sold in the DM corresponds to 31.157 MWh, while the foreseen one was expected to be 31.128 MWh.

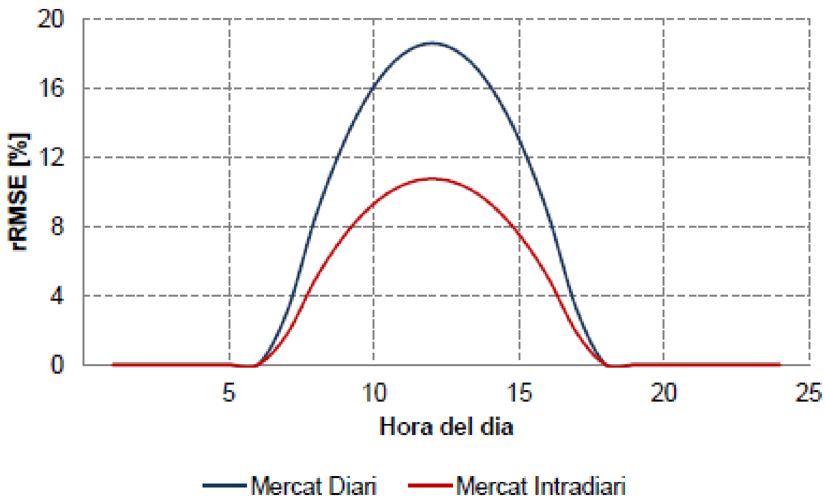

Fig. 4.10: RMSE trend during the day [10]

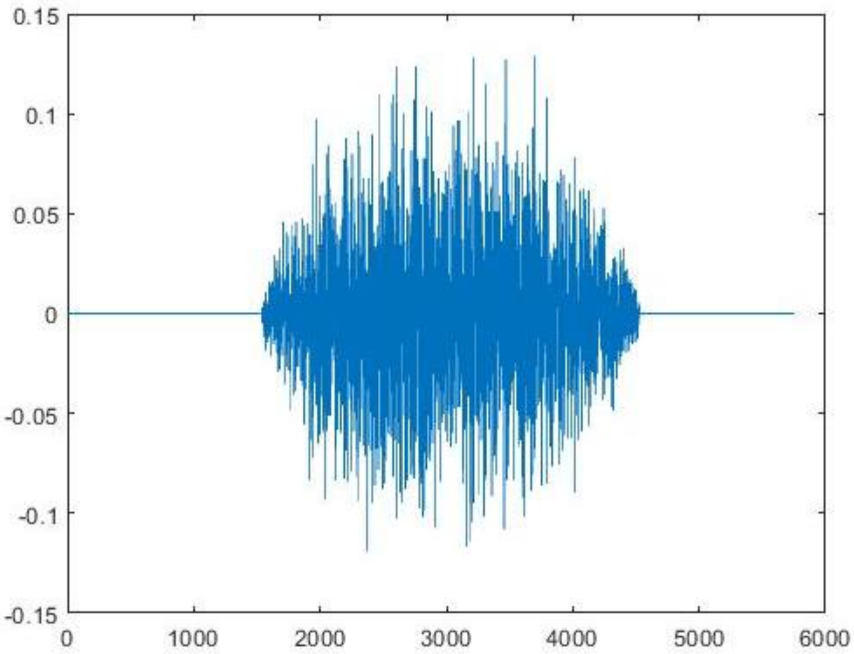

Fig. 4.11: Error

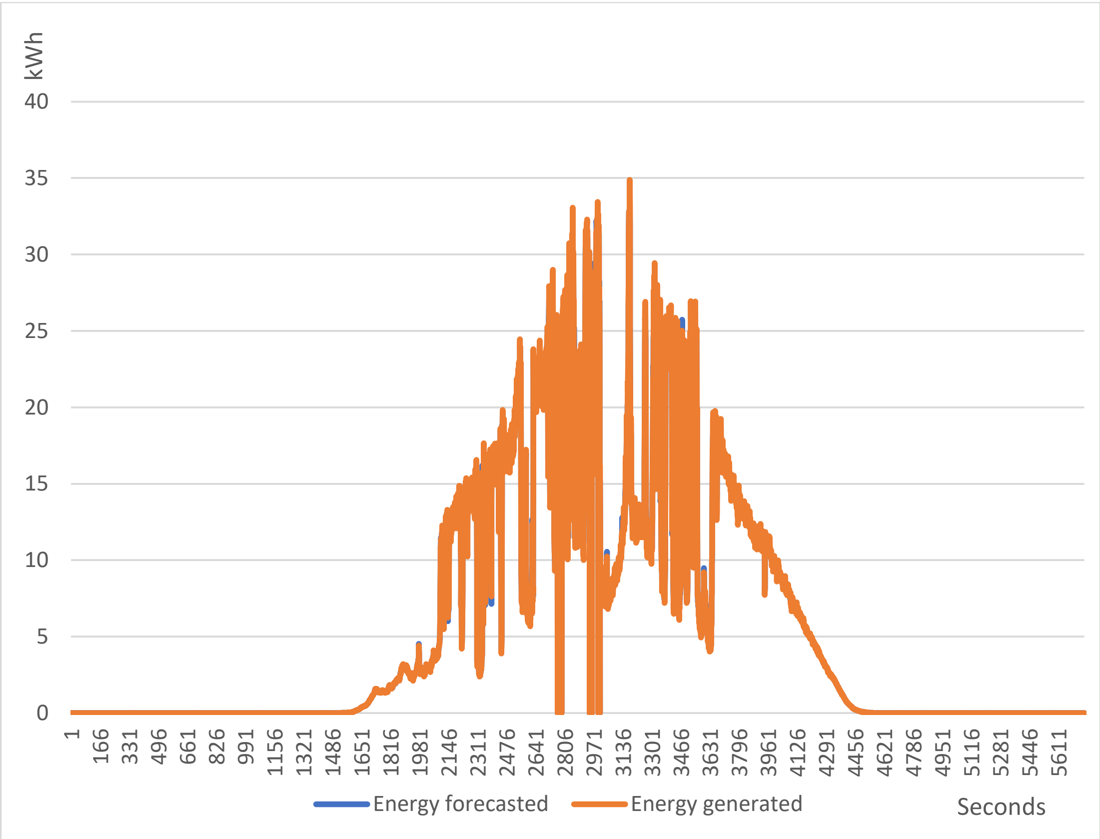

Fig. 4.12: Energy forecasted vs energy generated during the day in kWh

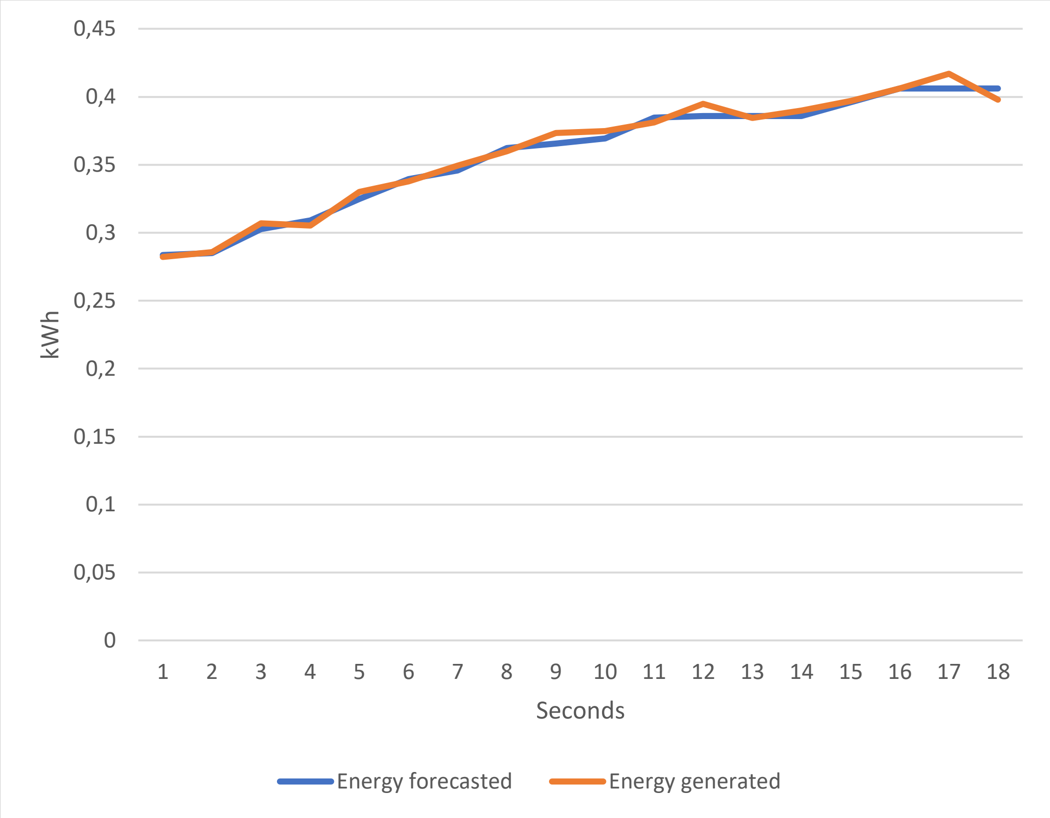

Fig. 4.13: Effective energy sold vs energy forecasted during the day in kWh *(zoom)*

- *Increasing deviation price,* λ_t^+ (€/MWh): taking into consideration the case in which the producer generates more than expected, but the system needs less energy, the surplus of energy is sold in the market at the increasing deviation price (PDSVS). As already seen, this price is always equal or lower than the marginal market price (as shown in Fig. 4.14), which means that the producer is selling the deviation with less profit than if his/her prediction was accurate. Data are taken from [47], which collected prices for each hour of the day. They are then adjusted in order to obtain 5760 values, in other words data measured every 15 seconds in a day.

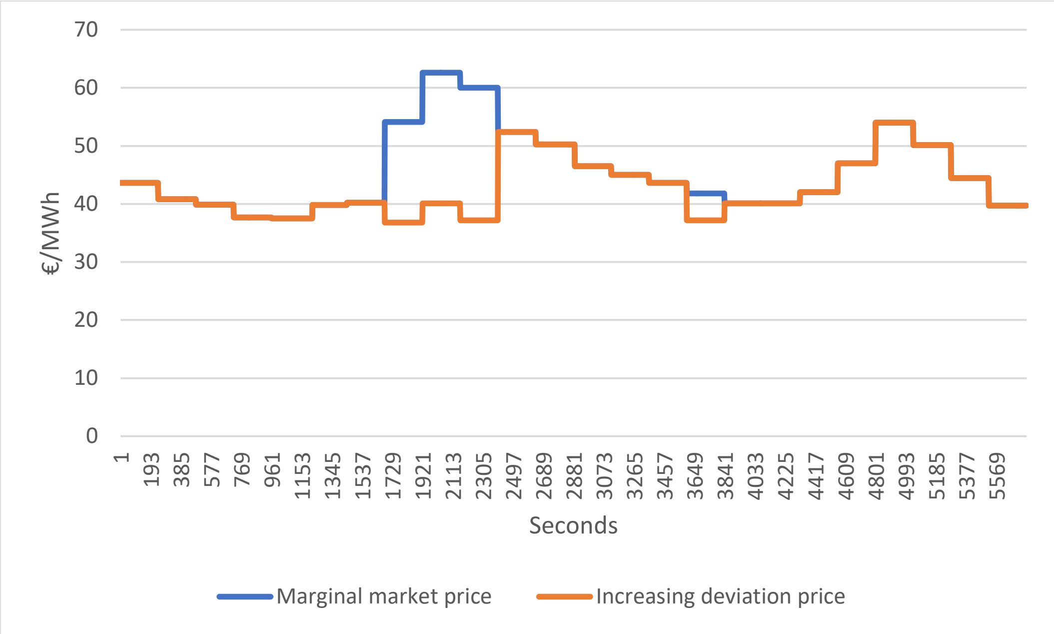

Fig. 4.14: Increasing deviation price vs marginal market price in €/MWh

- *Decreasing deviation price,* λ_t^-(€/MWh): taking into account the scenario in which the producer generates less than expected and the system needs more energy, he/she has to pay the energy deviation at the decreasing deviation price (PDSVB). So, in this case, the income is negatively affected by the incorrect forecasting made. It is considered a penalization, since the SO has to pay some extras to other generation units in order to provide the energy needed by the system that the power plant is not able to produce. In Fig. 4.15, it is possible to observe that the PDSVB is always equal or higher than the marginal market price. As explained for the increasing deviation price, data are taken from [47], which collected prices for each hour of the day. They are then adjusted in order to obtain the 5760 values needed. In Fig. 4.16, instead, it is possible to observe graphically the difference between increasing and decreasing deviation price.

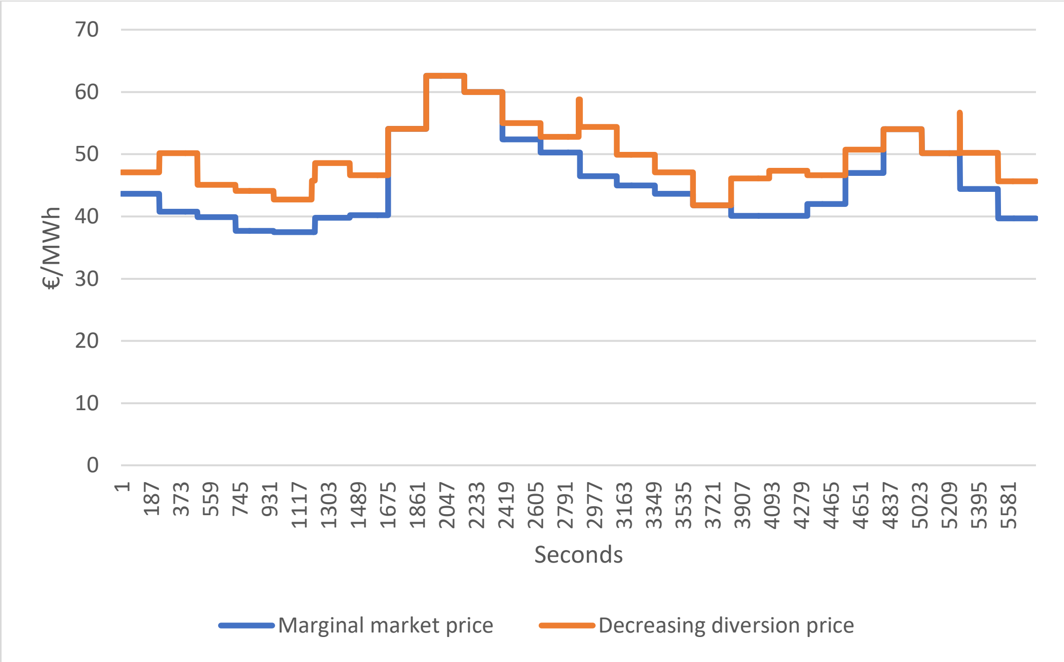

Fig. 4.15: Decreasing diversion price vs marginal market price in €/MWh

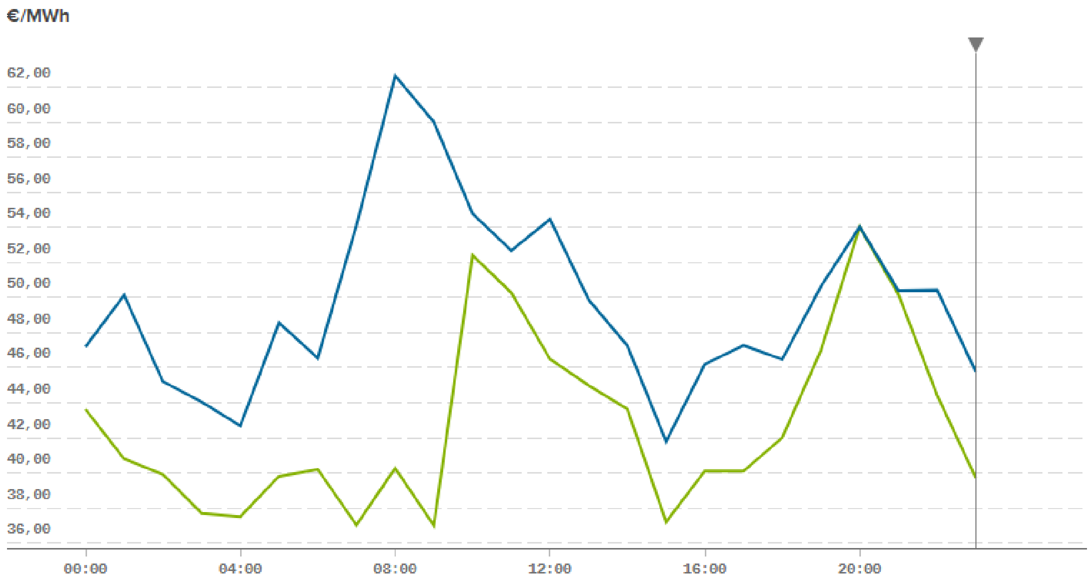

Fig. 4.16: Increasing deviation price (green) and decreasing diversion price (blue) [47]

- *System necessity,* N_t: this parameter corresponds to a binary data, which is 1 if the system needs more energy and 0 if the system needs curtailments. In order to obtain this information, the frequency variation data collected for the previous optimization are used. When the frequency is below the limits fixed by the Spanish grid codes, it means that the system necessity is 1, indeed the power plant is providing primary reserve to restore the balance between generation and demand. In the contrary, when the frequency overcomes the values fixed by the SO, the system necessity is 0, thus the curtailment of energy for primary reserve control. In this way, the binary vector concerning the system necessity is obtained with data collected for each 15 seconds during the day.

5. OPTIMIZATION RESULTS

5.1. Primary frequency control

In this section, the final results of the first optimization process are discussed. The system under study is analysed under two different situations:

- the PV power plant is equipped with battery energy storage system;
- the PV power plant does not offer storage.

The corresponding incomes for the provision of frequency response are compared, highlighting the optimal configuration. Moreover, it is important to underline that, in the case that the PV system without storage is not able to provide all the reserves needed for the stabilization of the network, this configuration receives anyway the incomes related to the availability fee, since the system is still providing the service according to its feasibility.

Table 5.1 shows GAMS optimization results for the two different configurations.

Table 5.1: Optimization results

Configuration	Income (€)	Battery capacity (kWh)	Inverter capacity (kW)
No energy storage	8.6780538×10^6	-	-
Energy storage	$\mathbf{10.76067 \times 10^6}$	$\mathbf{344.428699}$	$\mathbf{607.191655}$

As it can be seen, the PV system configuration with batteries enhances greater income, accounting for an adding value of almost 2.08 M€ respect to the system with no storage implementation. Concerning the size of the battery, the optimal configuration in order to maximise the power plant income corresponds to an installation of around 345 kWh, with an inverter of around 608 kW. These sizes are reasonable for a PV installation of 5 MW, as the case analysed; they are indeed in accordance with the current commercialised battery systems, such as the ones offered by Saft 100, with its Intensium Max energy storage system for renewables, as well as Fluence, both providing Li-ion batteries for PV power plants with similar purposes [54] [55].

Looking at Fig. 5.1 and Fig. 5.2, it is possible to better understand why the energy storage system provides the most convenient scenario. To do this, first of all, it is important to define the data that appear in the figures, each of them characterised by a specific colour:

- Blue (data1): it is the frequency response provision (kWh) needed for network frequency stabilization; negative values stand for high frequency event, which means that the PV system has to curtail that amount of reserve. In the contrary, positive values refer to low frequency event, so the installation has to provide that amount of energy.

- Red (data2): it is the energy discharged from the PV panels (kWh), which means an increase in their energy output in case of low frequency event.
- Yellow (data3): it is the energy charged to the PV panels (kWh), which means a decrease in their energy output in case of high frequency event.
- Violet (data4): it is the energy entering in the storage system (kWh).
- Green (data5): it is the energy discharged by the storage system (kWh).
- Light blue (data6): it is the usable charge level in the battery (kWh).

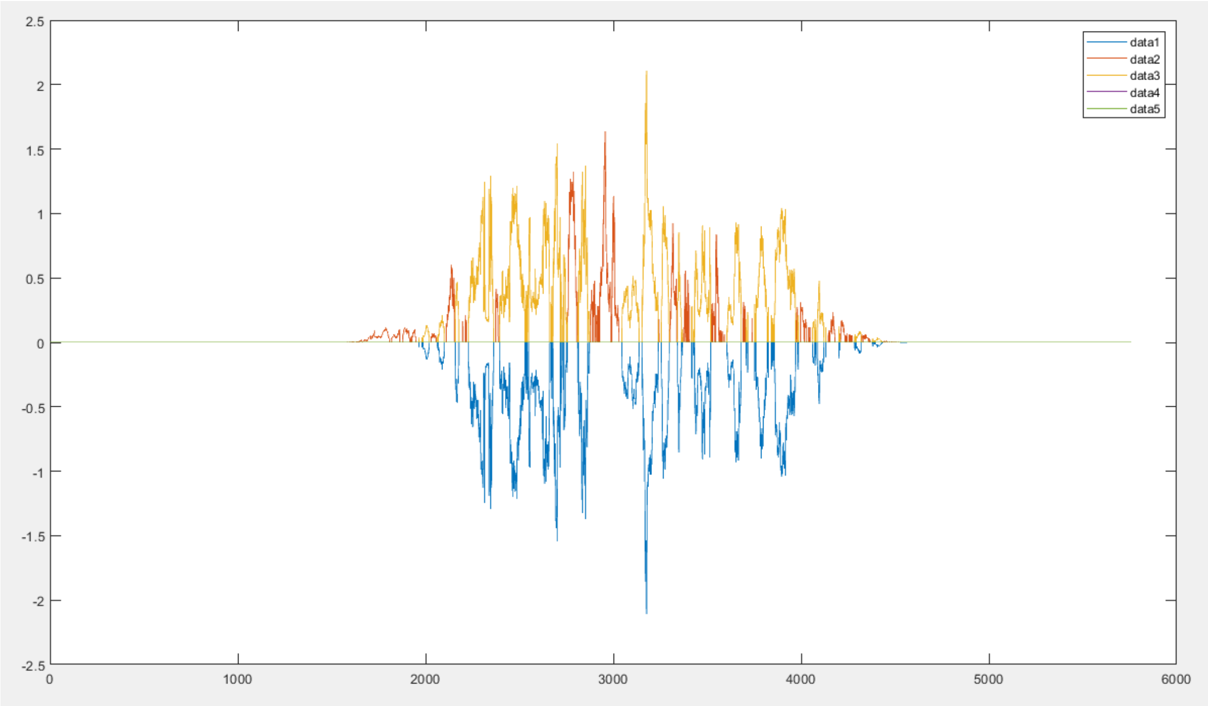

Fig. 5.1: Reserve provision with no storage

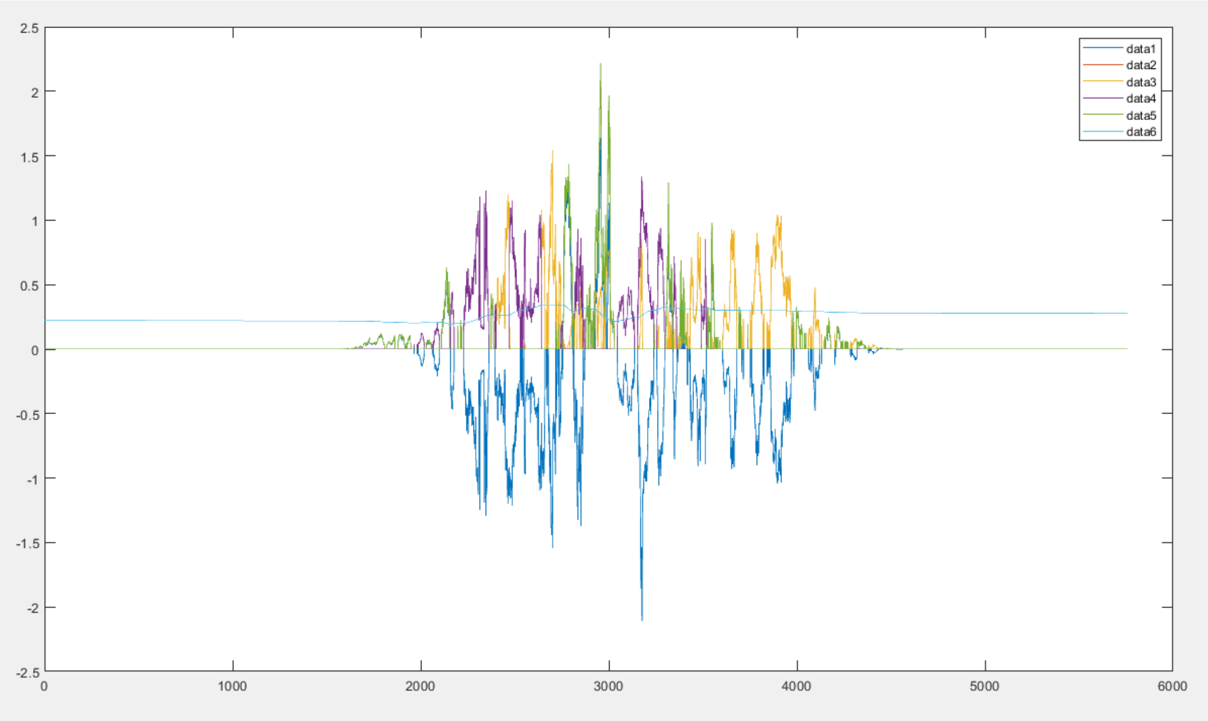

Fig. 5.2: Reserve provision with storage

As represented in Fig. 5.1, which shows the configuration of the system with no battery implementation, low and high frequency events are managed by increasing and decreasing the PV panels output. For the system equipped with batteries (Fig. 5.2), instead, in the case of reserve needed to increase the frequency (low frequency event in the network), the PV panels are not providing the service, that is totally furnished by the batteries, thus allowing the PV power plant to always work at its maximum power point. In the case of power curtailment (high frequency event in the network), instead, the system with storage first provides primary reserve control with the battery device until its full charge, and then it decreases the output power of the PV panels, thus avoiding energy losses which can be used for future low frequency events.

Finally, in Fig. 5.3, it is described the trend of the State of Charge (SoC) of the battery energy storage system during the day; as it can be seen, it fluctuates between 55% and 100% of its charge, never leaving the battery discharging below its half capacity.

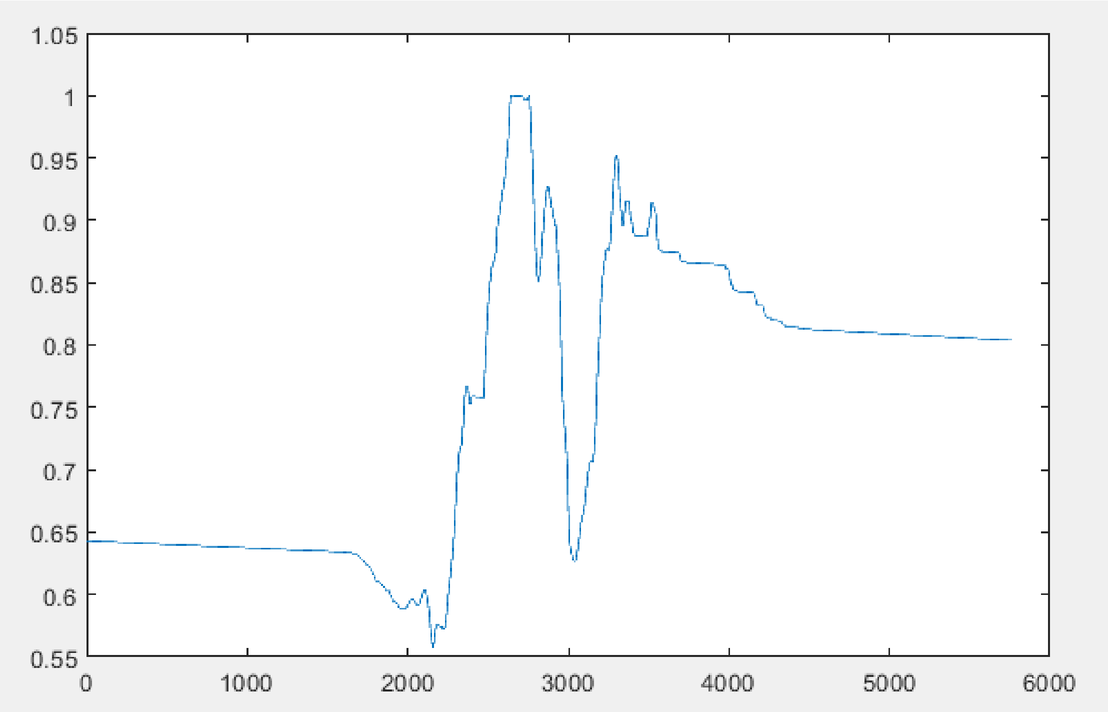

Fig. 5.3: State of charge of the battery during the day in %

5.2. Forecasting errors adjustment

In this section, final results of the second optimization process are discussed. The system under study is analysed for two different scenarios:

a) The PV power plant is equipped with a battery energy storage system, but this device is only controlling the primary frequency response issues. In other words, it is providing energy reserves for frequency stabilization, but it is not taking part in the forecasting error correction.
b) The PV installation is equipped with batteries for both ancillary services: primary frequency response and forecasting errors detection.

Taking as a reference the base case, in which the power plant is selling all the energy generated without incurring in forecasting errors during the DM scheduling, the corresponding incomes of the different configurations are compared, highlighting the optimal case (Table 5.2).

Table 5.2: Total income comparison

Configuration	Total income (€)	Battery capacity (kWh)	Inverter capacity (kW)
Base case	10.76067×10^6	344.428699	607.191655
Scenario a	10.54078×10^6	345.870253	606.749986
Scenario b	$\mathbf{10.82113 \times 10^6}$	**332.539989**	**647.065351**

As shown in Table 5.2, the forecasting errors commission for the energy scheduling in the DM (scenario a) obviously decreases the ideal base case, in which all the energy generated is selling in the market. In fact, generally, because of the unpredictability of the solar resource, the producer incurs in

deviations, which are economically penalised by the SO, thus reducing the income of the power plant if there is no storage device implemented. In this case, the penalty is around 220000 € (difference between base case and scenario a).
If the PV power plant is equipped with an energy storage system, batteries in this case, providing both frequency response and forecasting error adjustment (scenario b), the income significantly increases, seeing the producer earning 280000 € more respect to scenario a (3% more). It is clear that scenario b represents the optimal configuration, where the power plant income is even overcoming the ideal base case, since the real energy generated results being higher than the forecast made by the producer, thus allowing more energy sold in the DM. Furthermore, penalizations are totally avoided, since batteries are managing the forecasting errors charging and discharging according to the system need: when the production is higher than the forecast, the energy excess that is not sold in the market charges the battery, in the contrary, the energy loss is covered discharging the battery.

Concerning the size of the storage system, the optimal configuration, in order to maximise the power plant income, corresponds to an installation of around 333 kWh, with an inverter of around 648 kW. So, to enhance both services, frequency control and forecasting error detection, the power plant requires a smaller battery than the scenario a. This result is due to the fact that summing charging and discharging processes for both services at time t, the resultant battery is charging and discharging less than considering the case with only frequency response. An example can be that the storage system is charging for forecasting errors, while discharging for frequency response at the same time, and this implies a final energy charged (positive) of discharged (negative) smaller than considering the services separated.

In any case, the fact that the sizes of the battery and related inverter in both scenarios are similar means that the impact compensating the forecasting error can be considered minimum in the selection of the battery size, since the dimension is determined mainly from the frequency control service.

Fig. 5.4 and Fig. 5.5 show graphically how the batteries work in order to adjust the energy deviation produced. To better understand the process, it is first necessary to indicate the parameters under analysis, each of them related to a specific colour:

- Blue: it is the energy forecasted by the producer and scheduled to be sold in the DM, (kWh);
- Orange: it is the effective energy generated by the power plant (kWh);
- Grey: it is the energy charged in the storage system (kWh);
- Yellow: it is the energy discharged by the storage system (kWh).

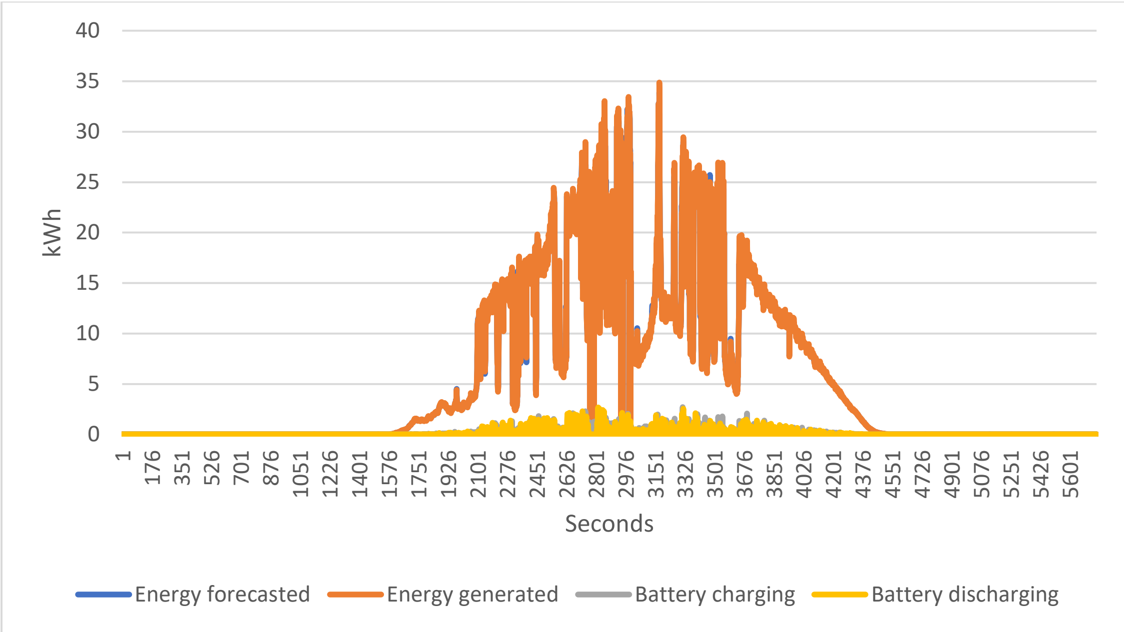

Fig. 5.4: Forecasting error adjustment with energy storage

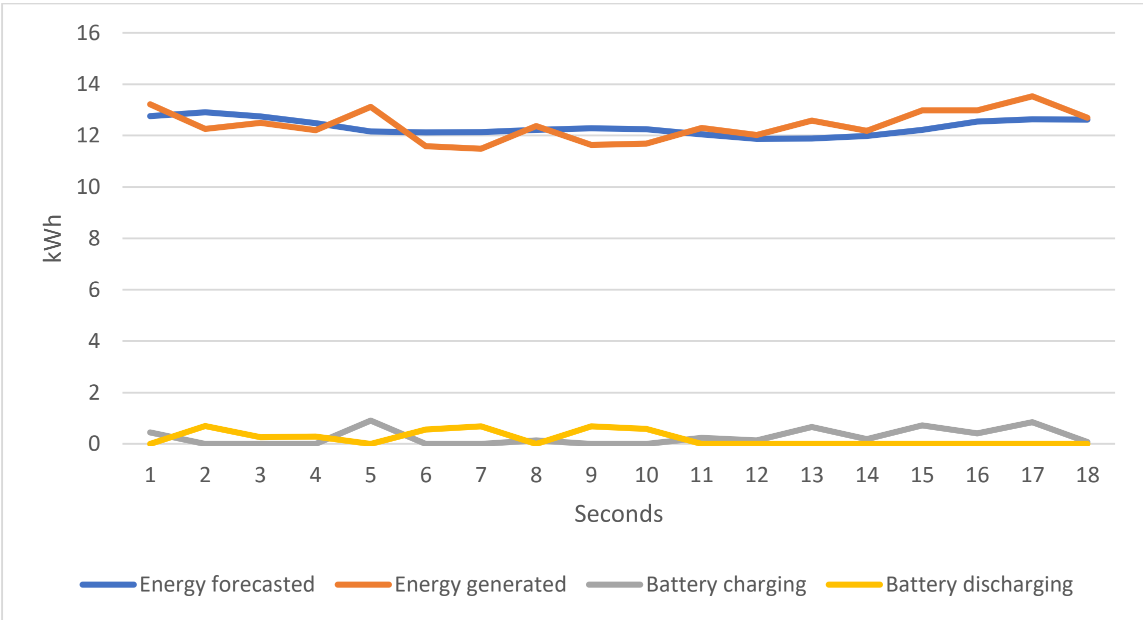

Fig. 5.5: Forecasting error adjustment with energy storage (zoom)

Finally, in Fig. 5.6, it is possible to observe the SoC of the batteries system, which fluctuates between 75% and 100% during the day, without leaving the device discharging less than its 3/4 of capacity.

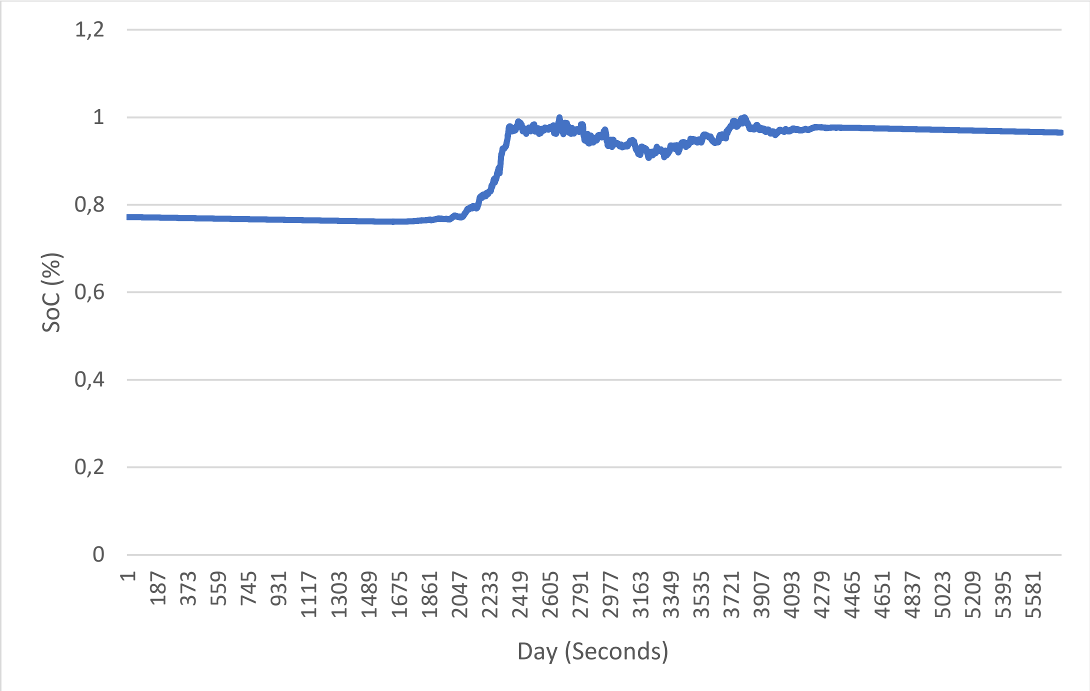

Fig. 5.6: Battery SoC during the day (%)

6. PROJECT BUDGET

A project budget can be defined as the total projected costs to complete a project during a specific period of time with a specific result. It is necessary to include several components, such as direct and indirect costs, fixed and variable costs, labour and materials, travel expenses, equipment needed, licences and so on.

6.1. Human resources costs

In this specific case, the project has been developed within 6 months and it can be structured in different tasks:

- Research and investigation: it refers to the collection of information for the development of the project;
- Tool modelling: it represents the design phase of the optimization process, which means the construction and development of the codes used;
- Simulation: in this task results are compared and validated, extrapolating the optimal strategy;
- Writing: it is referred to the following report development.

Each of them is characterised by the time spent in order to reach the defined goals. Table 6.1 shows the dedicated hours of work for each task.

Table 6.1: Time spent for the project development

Task	Dedicated time (h)
Research and investigation	200
Modelling	100
Simulation	50
Writing	150
Total	**500**

Considering that generally the base salary for an internship is around 8 €/h, the total human resources cost is 4000 €.

6.2. Software and hardware utilization costs

Concerning the equipment and software used for the development of the project, Table 6.2 shows the price of the computer needed, as well as the price of the programme used with related licence: Matlab and GAMS.

The official web site of Matlab offers different price options, according to the end user characteristics: standard, academic, home and student [56]. In this specific case, an academic profile for an annual licence has been chosen.

GAMS also offers prices for the base module require and the licence for single and academic users, with accurate information about solvers prices [57]. In this case, IPOPT and SCIP have been used.

Finally, the computer used is an ASUS E402MA laptop with 3 years of use.

Table 6.2: Price per unit for laptop and software

Equipment/Software	Price (€)
ASUS E402MA laptop	350
Matlab R2017b	250
GAMS 24.7	1650

The total matlutilization price is calculated as expressed in Equation 6.1:

$$Cost_{H+S} = \frac{Hours\ dedicated}{3\ \text{years}} \times \frac{1\ \text{year}}{8760\ \text{h}} \times cost_{laptop} + \frac{Hours\ dedicated}{1\ \text{years}} \times \frac{1\ \text{year}}{8760\ \text{h}} \times cost_{licences}$$

Equation 6.1

In conclusion, the total cost for the implementation of the problem is shown in Table 6.3:

Table 6.3: Total cost of the project

Cost	Price (€)
Human resources	4000
Hardware & Software	418.76
Total	**4418.76**

7. ECONOMIC ANALYSIS

In order to define if a determined project is profitable or not, it is necessary to calculate and analyse the main financial parameters:

- Cash flow (Q_t): it is the list of values, per period, accounting the difference between receipts (income) and payments (expenses).
- Investment: it represents an immediate payment for future receipts.
- Discount rate (*i*): it is the percentage of the money invested that the producer wants to gain annually.
- Net Present Value (*NPV*): it is an indicator of profitability and it is defined as the actualized sum of cash flows in each period (*t*) through the horizon of the project (*T*), as expressed in Equation 7.1. A positive NPV means that the investment is profitable.

$$NPV = \sum_{i=0}^{T} \frac{Q_t}{(1+i)^t}$$

Equation 7.1

- Internal Rate of Return (IRR): it is an indicator of risk and it is the discount rate at which the NPV becomes 0. It indicates the relationship between each euro earned per each euro invested.
- Payback: it is the time to reach positive cumulative cash flow (initial investment recovering).

In this case, the main objective is the evaluation of the profitability of the PV system equipped with a battery bank, in order to provide primary frequency response and forecasting error management.

In Table 7.1, it is possible to observe the values obtained for the calculation of income, expenses and cash flow within 15 years, which is the life-time of the battery bank installed in the project. The first one is related to the electricity sold in the DM and the incomes related to the contribution of primary reserve provision and forecasting error management, both implemented by the energy storage system. The second one includes in year 0 the investment related to the battery bank implementation (calculated as expressed in $C_s = \lambda_{pwr} S_{pwr} + \lambda_{cap} S_{cap}$)) and the costs associated to the power plant construction (deducted from [58]), while in the following years it represents the operation and maintenance costs (OPEX) of the batteries (calculated as expressed in $C_{deg} = (\varepsilon_{lc,t} + S^{-}_{fr,t} + S^{+}_{fr,t} + S_{loss,t}) \cdot \lambda_{deg}$)).

Table 7.1: Income, expenses and cash flow values within 15 years

Year	Income (€)	Expenses (€)	Cash flow (€)
0	0	4215928.9	-4215928.9
1	698689.9	19195.3	679494.6
2	698689.9	19195.3	679494.6
3	698689.9	19195.3	679494.6
4	698689.9	19195.3	679494.6
5	698689.9	19195.3	679494.6
6	698689.9	19195.3	679494.6
7	698689.9	19195.3	679494.6
8	698689.9	19195.3	679494.6
9	698689.9	19195.3	679494.6
10	698689.9	19195.3	679494.6
11	698689.9	19195.3	679494.6
12	698689.9	19195.3	679494.6
13	698689.9	19195.3	679494.6
14	698689.9	19195.3	679494.6
15	698689.9	19195.3	679494.6

From these data, it is now possible to determine the values of NPV, according to different discount rates, through the formula shown in Equation 7.1. Results are shown in Table 7.2. It is clear that the IRR is equal to 13.799%. Finally, the payback time is determined analysing the cumulative cash flow, which becomes positive in 7 years (Fig. 7.1).

Table 7.2: NPV values for different i

Discount rate (%)	NPV (€)
0	5976489.76
1	5153761.48
2	4426545.06
3	3782362.37
4	3210533.70
5	2701897.55
6	2248576.98
7	1843784.34
8	1481657.80
9	1157123.98
10	865782.58
11	603808.96
12	367.871,92
13	155064.09
13.799	**0**
14	-37157.11

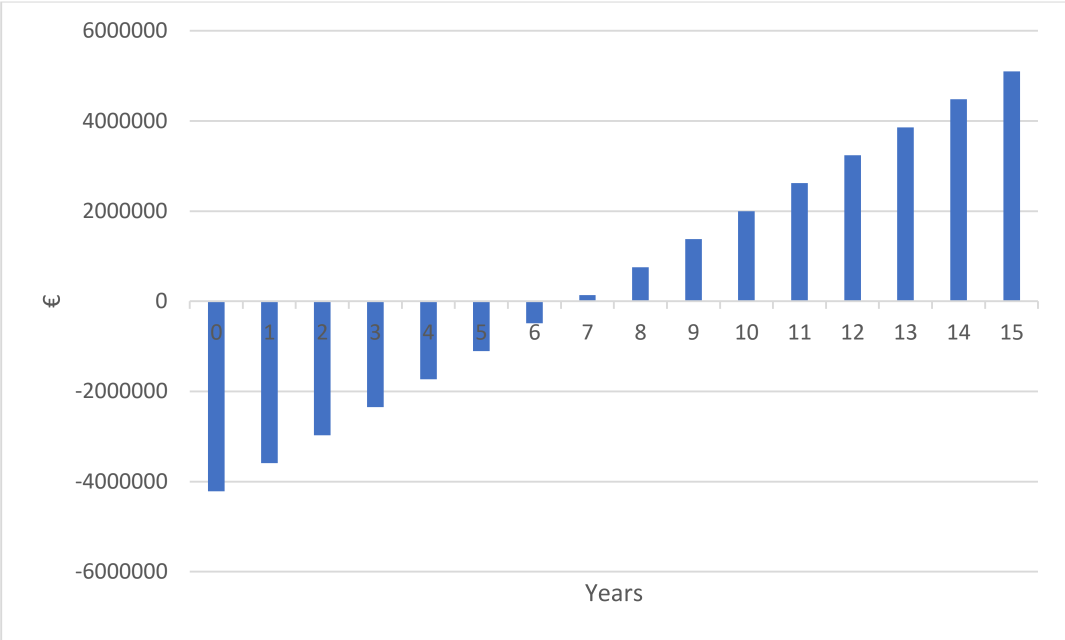

Fig. 7.1: Payback time

8. ENVIRONMENTAL IMPACT

The main objective of this project is the implementation of a battery bank in a PV power plant for primary frequency support and for the reduction of forecasting errors, thus increasing the penetration of solar energy in the Spanish electricity market. These two processes are strictly related to the decrease of fossil fuel dependence, as well as the reduction of CO_2 emissions in the atmosphere.

8.1. Primary frequency response

As already discussed, primary support can be provided for high or low frequency event: in the first one, the network needs curtailments in the energy production in order to decrease the frequency, instead, in the second one, the grid requires more energy generation to increase the network frequency until its normal value.

In this particular case, in order to determine the CO_2 savings by providing the service with no environmental impacts (the life cycle assessment of the batteries system is not taken into account), it is only analysed the support for low frequency event in the network. To do that, it is necessary to study the electricity mix and power installed by technology in Spain (Fig. 8.1 and Table 8.1).

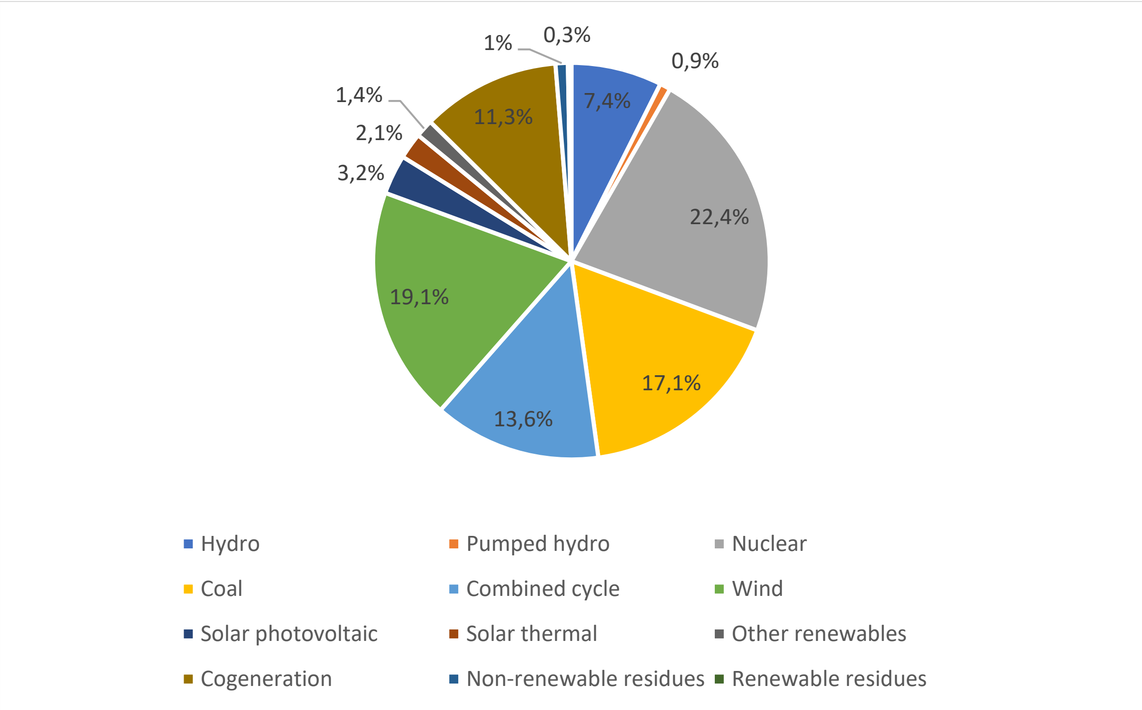

Fig. 8.1: Contribution of electricity demand by sector in Spain in 2017 [59]

Table 8.1: Energy installed by technology

Technology used	Power installed (GW)
Hydro	17.0
Pumped hydro	3.3
Nuclear	7.1
Coal	9.5
Combined cycle	24.9
Wind	22.9
Solar photovoltaic	4.4
Solar thermal	2.3
Other renewables	0.9
Cogeneration	5.8
Non-renewable residues	0.5
Renewable residues	0.1
Total	**98.7**

The carbon intensity of electricity production in Spain changes continuously, according to the electric energy mix. For this reason, an average represented value of $300\mathrm{g}_{\mathrm{CO_2eq}}/\mathrm{kWh}$ has been selected, based on [60].

Taking into account the energy reserves provided by the PV power plant equipped with batteries (Fig. 8.2), it is important to specify that the reserves contribution is totally provided by the storage system without affecting the PV panel production.

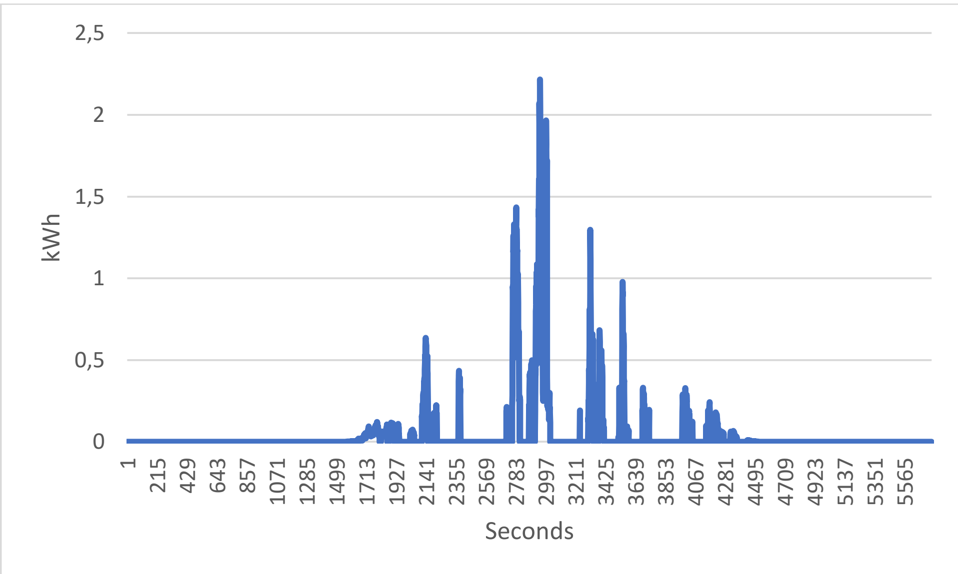

Fig. 8.2: Energy reserve discharged from batteries for low frequency event support

During the day, a total of 253.72 kWh of energy reserve is provided. This means that, considering a battery-lifetime of 15 years, the total $\mathrm{CO_2}$ saving from providing the service by a PV power plant is (see Equation 8.1):

$$CO_{2\,saving} = \frac{300g_{CO_2eq}}{kWh} \times \frac{253.72kWh}{day} \times \frac{365day}{year} \times 15years = 416.735tCO_{2\,eq}$$

Equation 8.1

Considering that in Spain the total installed capacity of PV is around 4.4 GW (as shown in **Error! Reference source not found.**) and supposing to implement a battery storage system in each installation, there would be a total CO_2 saving in the country of $366727tCO_{2\,eq}$.

8.2. Forecasting error

The deviation management market is based on the provision of the energy, which the producer is not able to produced, due to forecasting errors made in the schedule of the energy sold in the DM. In order to manage the deviation, the SO asks to other power plants to contribute in its correction providing the missing energy. In Spain, the major managers of forecasting error adjustment are divided according to the type of deviation occurred: if increasing, coal-fired power plant and then hydro account for 35 and 23%, while if decreasing, pumped-hydro and then coal-fired account for 38 and 26%, as shown in Fig. 8.3.

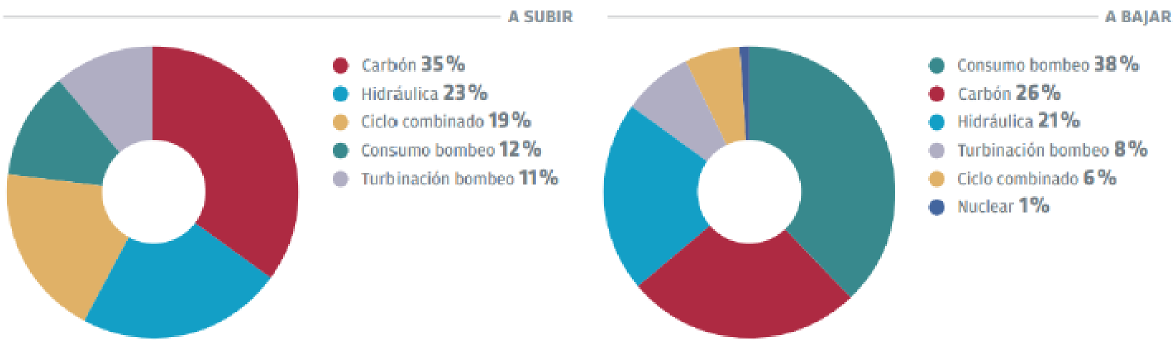

Fig. 8.3: Deviation management by technology (2013) [50]

In this project, the PV power plant under analysis has been equipped with a battery bank in order to reduce the forecasting errors made by the producer. Since this service is provided by a non-pollutant device (the life cycle assessment of the battery is not taken into account), there will be savings in the production of CO_2 emissions, compared with the other technologies that provide this type of service.

From literature [61], the carbon intensity related to the electricity production in coal-fired and combined-cycle power plants are shown in Table 8.2. Respect to the other technologies used, hydropower, pumped-hydro and nuclear are assumed to be no-polluting.

Table 8.2: Carbon intensity by technology for deviation management

Technology	Carbon intensity (g_{CO_2eq}/kWh)
Coal-fired	900
Pumped-hydro	0
Combined-cycle	350
Nuclear	0

The results obtained by GAMS indicate the values of the increasing and decreasing deviations managed by the battery bank during the day. Data are shown in Table 8.3.

Table 8.3: Increasing and decreasing deviation results

Increasing deviation (kWh)	443.4043
Decreasing deviation (kWh)	440.9886

Taking into account the contribution of each technology in percentage, previously shown in Fig. 8.3, the amount of increasing and decreasing deviation managed by the system is obtained (Table 8.4). These values are then multiplied by the carbon intensity amount in order to obtain the CO_2 saving related to the provision of the service by the PV power plant, or better, by the energy storage system implemented (Table 8.5).

Table 8.4: Real data for the contribution of deviation managed by technology

Technology	Increasing deviation (kWh)	Decreasing deviation (kWh)
Coal-fired	155.191	114.657
Pumped-hydro	155.191	260.183
Combined-cycle	84.247	26.459
Nuclear	0	4.410

Table 8.5: CO2 savings

Technology	$CO_{2\ savings}(gCO_{2eq})$	
	Increasing	Decreasing
Coal-fired	139.672	103.191
Combined-cycle	29.486	9.260
Total	**169.158**	**112.451**

Finally, taking into account the life-time of the battery bank, the total CO_2 saving is determined in Equation 8.2:

$$CO_{2\ saving} = (169.158 + 112.451)\frac{\mathrm{gCO_{2\ eq}}}{\mathrm{day}} \times 365\mathrm{days} \times 15\mathrm{years} = 1.542\mathrm{tCO_{2\ eq}}$$

Equation 8.2

8.3. CO_2 saving implemented

As the PV power plant provides both services, in conclusion, it is calculated the total CO_2 saving considering a battery lifetime of 15 years, while the storage device is contributing to frequency support and forecasting error management (see Equation 8.3).

$$CO_{2\ saving} = 416.735\mathrm{tCO_{2\ eq}} + 1.542\mathrm{tCO_{2\ eq}} = 418.277\mathrm{tCO_{2\ eq}}$$

Equation 8.3

9. CONCLUSION

This work has presented a methodology for the economic optimization of the sizing of an energy storage system for a PV power plant installation, with the main objectives of enhancing primary frequency control in the grid and decreasing forecasting errors.

As previously explained, the scenario under analysis is the Spanish market. However, for the first optimization process, related to primary frequency control, the UK regulation and remuneration scheme have been taken as a reference. In the case of the forecasting error management, instead, the Spanish electricity market has been selected, since it is active in this purpose and offers all the data needed for the implementation.

Frequency support service through energy storage implies an added income to the power plant profit, since it allows its normal operation near the maximum power point, exploiting all the solar resource available in a specific moment. Furthermore, the SO normally offers a base remuneration to those producers available for frequency support services (the availability fee, λ_{av}), regardless of they end up providing them or not.

Concerning forecasting error management, this service also accounts for economic benefits, since penalties are avoided, thanks to the storage device, which adjusts to higher and lower generations according to the system needs.

The provision of both services requires the use of a battery bank sized at less than the 7% of the power plant rated power, in order to accomplish an optimal operation.

The positive results obtained suggest that the UK's strategy, based on opening a tender process and letting power plants -including renewables and energy storage- participate in exchange of appropriate remuneration, could be a leading example for a near future scenario in which Spain could be considerably benefited.

In addition, it is expected that batteries prices will consistently decrease in the following years, due to the discovery and development of new, cheaper and more environmentally-friendly materials, able to maintain the same properties even at higher efficiencies.

All these facts imply that it is only a matter of time that energy storage will play a key role in the totally integration of renewables in the electric grid, thus supporting network stability and contributing to the decarbonisation of the economy.

The scope of this work has been limited to the analysis of one day, because of GAMS computational limits. Next steps would be the extension of the study to the whole year, making more realistic the behaviour of the PV plant production according to seasonal changes. Furthermore, other services may be involved, as secondary and tertiary reserves, as well as IM forecasting error management.

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